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PV SOLAR SYSTEM CONTROL AS (PV-STATCOM) FOR POWER OSCILLATION DAMPING

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ABSTRACT

This Project is based on a novel control of PV solar system as a FACTS device STATCOM, termed PV-STATCOM, for power oscillation damping (POD) in transmission systems. In the proposed control, as soon as power oscillations due to a system disturbance are detected, the solar farm discontinues its real power generation function very briefly (few tens of seconds) and makes its entire inverter capacity available to operate as a STATCOM for POD. As soon as power oscillations are damped, the solar farm restores real power output to its pre-disturbance level in a ramped manner, while keeping the damping function activated. This results in much faster restoration than that specified in grid codes. During nighttime, the solar farm performs POD with its entire inverter capacity. It is shown from EMTDC/PSCAD simulations that the proposed control provides significant increase in power transfer capacity on a 24/7 basis in systems which exhibit both local inertial and inter-area oscillatory modes. The proposed PV-STATCOM is about 50-100 times cheaper than an equivalent STATCOM for providing POD at the same location. This novel control can potentially bring large savings for transmission utilities and open up a new revenue making opportunity for solar farms for providing POD.

CHAPTER-1

INTRODUCTION

LOW frequency electromechanical power oscillations (typically 0.1 - 2 Hz) are recognized as one of the major limiting factors in power transfer over long transmission lines [1]. Conventionally, these oscillations are damped by Power System Stabilizers (PSS) integrated with synchronous generators [1]. However, Flexible AC Transmission System (FACTS) devices have been effectively utilized in power systems for damping these power oscillations and thereby enhancing the power transfer capability in transmission lines [2-4]. Performances of various FACTS devices equipped with power oscillation damping (POD) controllers are described in literature, such as, Static Var Compensators (SVC) [5], Static Synchronous Compensators (STATCOM) [6, 7], Thyristor Controlled Series Compensators (TCSC) [8], and Convertible Static Compensator (CSC) Large scale PV solar farms in excess of 100 MW are being increasingly connected worldwide. These include Kamuthi (648 MW), in Tamil Nadu, India [10], Rancho Cielo Solar Farm (600 MW), Solar Star I and II (579 MW), Topaz Solar Farm (550 MW), Agua Caliente Solar Project (295 MW) California Valley Solar Ranch Farm (250 MW) in USA, and Huanghe Hydropower Golmud Solar Park in China (200 MW) [11-13]. The potential of reduction in power system stability with significant amount of inertia-less power injection from PV solar plants in the grid is described in [14-16]. Smart PV inverter controls such as Constant (off-unity) Power Factor, Volt/Var, Volt/Watt, Frequency Watt, Low/High Voltage Ride Through, Low/High Frequency Ride Through, etc., have been proposed [17] and also demonstrated on a large scale PV solar farm [18]. A novel control of PV solar farm as STATCOM (PV-STATCOM) was presented for enhancing the connectivity of wind farms in the night [19] and for increasing power transfer capacity through damping of power oscillations both during night and day [20]. This control technique utilized the entire inverter capacity in the nighttime and the inverter capacity remaining after real power generation during daytime for power oscillation damping. An eighth-order POD controller for large PV solar farm was proposed in [21], whereas an energy function based design of POD controller was presented in [22]. Both these controllers are relatively complex in design. All the POD controls in the above papers [19-22] are based on remaining inverter capacity during daytime. Hence, the proposed POD capability of solar farm is limited during day, indeed becoming zero during hours of full sun. This paper proposes a novel PV-STATCOM control for POD, based on a patent-pending technology [23]. In this proposed control, if any disturbance occurs in the power system causing undesirable power oscillations, the PV solar farm autonomously disables its real power generating function for a short period (typically less than a minute), and makes its entire inverter capacity available for operating as STATCOM to damp power oscillations through reactive power modulation. As soon as the power oscillations are reduced to an acceptable level, the solar farm restores its power output to its pre-disturbance level in a ramped manner. Another novel contribution of this paper is that the POD function is kept activated during the ramp up of power to its pre-disturbance value utilizing the inverter capacity remaining after real power generation. This prevents any recurrence of power oscillations and also allows a much faster ramp-up than prescribed by grid codes [24] where such a damping function during ramp-up is not envisaged. While [19] and [20] have both presented the control of PV solar farm as STATCOM, [19] has dealt with voltage control only during nighttime (not daytime) on a distribution feeder. The damping of power oscillations in transmission systems is not examined at all. Power oscillation damping control in a Single Machine Infinite Bus (SMIB) transmission system is described in [20]. This control has been demonstrated during nighttime with full inverter capacity but during daytime with only partial inverter capacity. This STATCOM control has the following limitations: i) it is available only when there is remaining inverter capacity available after real power generation, and ii) its capability declines with increasing real power output from solar farm, becoming completely zero during hours of full sun. The novel smart PV inverter control as PV-STATCOM proposed in this paper is an altogether different control which allows power oscillation damping as follows: i) with full inverter capacity, and ii) both during night and day on a 24/7 basis. The effectiveness of the proposed PV-STATCOM for POD is demonstrated on a Single Machine Infinite Bus (SMIB) system [25], Two-Area power system [1], and the 12 bus FACTS power system [30] through detailed electromagnetic transients studies using PSCAD/EMTDC software. The Simplex optimization method embedded in PSCAD/EMTDC [26] is utilized to design the POD controller. In [27-29], the small signal Residue Analysis technique is presented for determining the most effective locations of power system stabilizer (PSS) in power systems. The same technique is utilized in this paper to investigate the effectiveness of specific PV-STATCOM locations for POD

1.1 LITERATURE REVIEW

IN "Y. XIAO, Y. SONG, C.-C. LIU, AND Y. SUN, "AVAILABLE TRANSFER CAPABILITY ENHANCEMENT USING FACTS DEVICES," IEEE TRANS. POWER SYSTEMS, VOL. 18, PP. 305-312, 2003." From the viewpoint of operational planning, this paper focuses on the evaluation of the impact of FACTS control on available transfer capability (ATC) enhancement. Technical merits of FACTS technology on ATC boosting are analyzed. An optimal power-flow-based ATC enhancement model is formulated to achieve the maximum power transfer of the specified interface with FACTS control. For better studying the capability of FACTS control, a power injection model of FACTS devices, which enables simulating the control of any FACTS devices, is employed. Studies based on the IEEE 118-bus system with all categories of FACTS devices demonstrate the effectiveness of FACTS control on ATC enhancement.DEREGULATION of the electric industry throughout the world aims at creating competitive markets to trade electricity, which generates a host of new technical challenges to market participants and power system researchers. For transmission networks, one of the major consequences of the nondiscriminatory open-access requirement is a substantial increase of power transfers, which demand adequate available transfer capability (ATC) to ensure all economic transactions. Sufficient ATC should be guaranteed to support free market trading and maintain an economical and secure operation over a wide range of system conditions. However, tight restrictions on the construction of new facilities due to the increasingly difficult economic, environmental, and social problems, have led to a much more intensive shared use of the existing transmission facilities by utilities and independent power producers (IPPs). These concerns have motivated the development of strategies and methodologies to boost the ATC of the existing transmission networks. As a result, power suppliers will benefit from more market opportunities with less congestion and enhanced power system security; it will be more profitable for transmission owners with maximized use of existing transmission assets; and customers will also get improved services and reduced prices. Aimed at this problem, various ATC enhancement approaches have been proposed, where adjusting terminal voltage of generators and taps changing of onload tap changer (OLTC), particularly rescheduling generator outputs, are considered as major control measures for ATC boosting [1], [2]. As discussed in the report of North American Electric Reliability Council (NERC)—Available Transfer Capability Definition and Determination [3], the ability of interconnected transmission network to reliably transfer power through prescribed interfaces may be restricted by thermal, voltage or stability limits. On the other hand, it is highly recognized that, with the capability of flexible power-flow control and rapid action, flexible ac transmission systems (FACTS) technology has a wide spectrum of impacts on the way the transmission system operates, in particular with respect to thermal, voltage, and stability constraints. From the perspective of steady-state system power-flow, circuits do not normally share power in proportion to their ratings, and in most situations, voltage profile cannot be smooth. Therefore, ATC values are always limited ultimately by heavily loaded circuits and/or nodes with relatively low voltage, with the increase of system loading. As stated in [4], FACTS concept makes it possible to use circuit reactance, voltage magnitude, and phase angle as controls to redistribute line flow and regulate nodal voltage, thereby mitigating the critical situation. In addition, partly due to the physical constraints on circuit impedance and phase angle of nodal voltage, most high-voltage transmission lines are operating far below their thermal rating [5]. By the control of line reactance and voltage phase angle, FACTS technology enables line loading to increase flexibly, in some cases, all the way up to thermal limits. Therefore, theoretically it can offer an effective and promising alternative to conventional methods for ATC enhancement. To resolve the emerging power system problems in the late 1980s, the Electric Power Research Institute (EPRI) proposed that besides flexible power-flow control over designated transmission routes, another major objective of FACTS applications is to increase the power-transfer capability of transmission systems [4]. In a 1997 EPRI report—FACTS Assessment Study to Increase the Arizona–California Transfer Capability [6], the technical advantages of FACTS technology for increasing the ATC of Arizona–California interface are assessed based on power-flow, transient stability, and sub synchronous resonance mitigation. The result indicates that use of the FACTS devices could increase the ATC as much as 1000 MW. As stated in a California Energy Commission report [7], among all of the major FACTS devices, the unified powe-flow controller (UPFC) is the most beneficial one for increasing import capacity into San Diego Gas and Electric's (SDG&E)'s service area. According to another EPRI report [8], FACTS control can increase the capacity of individual corridors by up to 80%, simply by shifting power-flow from overloaded to underloaded transmission lines. In addition to that, by improving system stability through their rapid-response capability, FACTS controllers in widespread use can also increase the overall capacity of a large transmission network by 20% or more. Undoubtedly, it is very important and imperative to carry out studies on exploitation of FACTS technology to enhance the ATC. Since comprehensive ATC evaluation and enhancement models that take into account stability aspects are still in the research and preliminary development stage, this paper only centers around steady-state ATC enhancement. An optimal power-flow (OPF)-based ATC enhancement model is formulated to achieve the maximum power transfer of the specified interface with FACTS control, where voltage limits and line thermal limits are considered. On the basis of the methodology proposed for improving ATC by the control of UPFC in [9], this paper focuses on quantitative evaluation of the impact of all categories of FACTS devices on ATC enhancement. For better studying the capability of FACTS control, a power injection model (PIM), which enables the implementation of the control of any FACTS device, is employed to derive the control parameters [10]. Finally, with the IEEE 118-bus system as a testing bed, case studies are conducted on all categories of FACTS devices. The results demonstrate the effectiveness of FACTS control on ATC enhancement.

IN “X. Y. BIAN, Y. GENG, K. L. LO, Y. FU, AND Q. B. ZHOU, "COORDINATION OF PSSS AND SVC DAMPING CONTROLLER TO IMPROVE PROBABILISTIC SMALL-SIGNAL STABILITY OF POWER SYSTEM WITH WIND FARM INTEGRATION," IEEE TRANS. POWER SYSTEMS, VOL. 31, PP. 2371-2382, 2016” A modified fruit fly optimization algorithm (MFOA) combined with a probabilistic approach are proposed in this paper to coordinate and optimize the parameters of power system stabilizers (PSSs) and static VAR compensator (SVC) damping controller for improving the probabilistic small-signal stability of power systems with large-scale wind generation, taking into consideration the stochastic uncertainty of system operating conditions. It is generally accepted that there is a threat to the stability of power system with penetration of wind farm. In addition, the stochastic fluctuations of wind generation make PSSs tuning more difficult. In this paper, PSSs and SVC damping controller are employed for suppressing local and inter-area low frequency oscillation. In order to eliminate the adverse effect between PSSs and SVC damping controller, the MFOA based on the probabilistic eigenvalue is applied to coordinate and optimize their parameters. The effectiveness of the proposed approach is verified on two test systems. I N recent years, the installation of renewable wind energy has expanded rapidly. Many large-scale wind farms are integrated to power grids through 110-kV or 220-kV transmission lines, which bring great and direct influence on the stability of main power networks. Impacts of large-scale wind power penetration on the power system stability have received much attention [1]–[3]. The random fluctuations of wind power output increase the uncertainty of system power balance [4], which will result in adverse effects on the system dynamic stability, especially the small-signal stability. It is important to analyze the power system small-signal stability with probabilistic methods [1], [5] and consider the effects of uncertainty of wind farm output and stochastic changes of loads. References [1], [6], and [7] represent some investigations along that line. Their work verifies the effectiveness of the probabilistic approach and illustrates that the integration of large-scale wind farms could cause the power system probabilistic small-signal instability that could be difficult to overcome. However, [1], [6], and [7] do not propose effective measures to improve the probabilistic small-signal stability, especially for damping the inter-area mode with wind power variations. Application of power system stabilizers (PSSs) is normally a first measure to enhance the system small-signal stability. Large-scale wind farm integration can induce a higher probability of system instability when compared to one without wind generation [6], [7]. Uncertain fluctuations of wind generator output also make PSSs tuning more difficult [8]. In some cases, when the use of PSSs cannot provide sufficient damping for inter-area power swing (0.1–0.7Hz), SVC damping controller is an alternative effective solution. The primary application of SVC in a power system with integration of wind farm is to maintain the busbar voltage and provide reactive power support [9], [10]. With a damping controller installed, SVC can provide extra damping [11], [12]. SVC and PSSs are all fast acting power controller devices. There is a potential possibility that these devices may interact adversely with each other and may not produce the expected performance. To improve their overall combined performance, it is necessary to coordinate and optimize the PSSs and SVC damping controller parameters. A few researches are made along that line [13]–[15]. However, [13] and [14] are based on linearized power system around certain specified operating points (i.e., deterministic). With a linearized model, controller settings which are able to stabilize the system around certain specified operating points may not perform satisfactorily at other points. In [15], the probabilistic eigenvalue sensitivity analyses are carried out for the design of PSSs and SVC damping controller for power system small-signal stability enhancement, without considering the stochastic fluctuations of wind power output. In the design of controller parameters, one single parameter usually influences more than one oscillation mode. The genetic algorithms (GAs) [16], [17] and the particle swarm optimization (PSO) [18] have been widely used as optimization tools. However, the GA requires long computational time and also suffers from premature convergence. The PSO may easily fall into and then be trapped at a local optimal point. The fruit fly optimization algorithm (FOA) [19], [20] has a high searching precision. It is simple and it has only a few parameters to be set but they can be easily adjusted. It also enjoys a high global search capacity. However, the FOA is not suitable for solving problems whose independent variables can have negative values. Thus a modified fruit fly optimization algorithm (MFOA) is proposed to avoid the limitation that variables of the fitness function are restricted to be in the zone of . In this paper, a probabilistic method based on numerical analysis is proposed to analyze statistical attributes of the smallsignal stability of the power system with grid-connected wind power source. The analysis takes into consideration multi-operating conditions including the stochastic variations of wind farm output, the random fluctuations of synchronous generator output, loads and nodal voltages variations. Plug-in modeling technology (PMT) [21] is adopted to construct the state matrix of the whole system. The SVC supplemented with damping controller and PSSs on synchronous generators are applied to increase the probability of stability. For coordinating and optimizing parameters of PSSs and SVC damping controller, the MFOA [22]–[24] is developed and applied.

IN “M. HAQUE, "IMPROVEMENT OF FIRST SWING STABILITY LIMIT BY UTILIZING FULL BENEFIT OF SHUNT FACTS DEVICES," IEEE TRANS. POWER SYSTEMS, PP. 1894- 1902, 2004.” —This paper proposes a new control strategy of shunt flexible ac transmission system (FACTS) devices to improve the first swing stability limit of a simple power system. It is shown that the speed based bang-bang control (BBC) is unable to use the entire decelerating area in maintaining stability. The proposed control strategy improves the stability limit first by maximizing the decelerating area and then fully utilizing it in counterbalancing the accelerating area. This requires to continue the operation of shunt FACTS devices at full capacitive rating until the machine speed reaches a reasonable negative value during the first return journey. Afterwards, the control can be switched to continuous type to improve system damping in subsequent swings. The proposed control strategy is then applied to both static var compensator and static synchronous compensators placed in a single machine infinite bus system. The same control strategy is also used for some faults in a multimachine system. In both the systems, it is found that the proposed control can provide significantly higher stability limit than that of the BBC. The mechanism of improving the stability limit is also described. TRANSIENT stability is the main factor that limits the power transfer capability of long distance transmission lines. Power utilities are now placing more emphasis on improving the transient stability, especially the first swing stability limit, to increase the utilization of existing transmission facilities. A power system can be considered as first swing stable if the post-fault angle of all machines in center of angle (COA) reference frame increases (decreases) until a peak (valley) is reached when the angle starts returning [1], [2]. In other words, existence of zero speed (maximum or minimum angle) of all machines guarantees the first swing stability of the system. In general, a first swing stable system is considered as stable because system damping, governor, etc. usually help to damp oscillation in subsequent swings [3]. The first swing stability limit of a single machine infinite bus (SMIB) system can be determined through equal area criterion (EAC) [4] that depends on the difference between input mechanical power and output electrical power of the machine. During faulted period, the output power of the machine reduces drastically while the input mechanical power remains more or less constant and thus the machine accelerates. The turbine delivers excess energy to the machine and that can be represented by an area called accelerating area. To maintain the first swing stability, the machine must transfer the excess energy to the network once the fault is cleared. The excess energy transferring capability of the machine can be represented by another area called decelerating area and it depends on post-fault network condition. The stability limit can be improved by enlarging the decelerating area in early part of post-fault period. Initially, it was considered that the network condition cannot be controlled fast enough to enlarge the decelerating area dynamically. However, recent development of power electronics introduces the use of flexible ac transmission system (FACTS) devices in power systems [5]. FACTS devices are capable of controlling the network condition in a very fast manner and this unique feature of FACTS devices can be exploited to enlarge the decelerating area and hence improving the first swing stability limit of a system Static var compensators (SVC) and static synchronous compensators (STATCOM) are members of FACTS family that are connected in shunt with the system [5]. Even though the primary purpose of shunt FACTS devices is to support bus voltage by injecting (or absorbing) reactive power, they are also capable of improving the transient stability and damping of a power system. The stability or damping can be improved by increasing (decreasing) the power transfer capability when the machine angle increases (decreases) and this can be achieved by operating the shunt FACTS devices in capacitive (inductive) mode [5], [6]. Continuous and discontinuous types of control are very commonly used for shunt FACTS devices to improve the transient stability and damping of a power system [6]–[10]. The continuous control may not utilize the full capability of the device. On the other hand, the discontinuous control operates the device at its full rating to provide the maximum benefit. The continuous control is found to be very effective in improving the dynamic stability problem caused by small disturbances. However, to improve the transient stability, much larger control action is needed and it is suggested that the discontinuous control (also called bang-bang control, or BBC) should be used for this purpose [6]. In BBC, the mode of operation of the device is changed (from full capacitive to full inductive or vice versa) at some discrete points. Usually the machine speed signal is used to change the mode of operation [5], [6] but any signal that is dynamically related to machine speed can also be used. References [7] and [11] used some locally measured signals to estimate the machine angle and speed of a simple radial system. However, the same techniques may not be applied to a general multimachine system. The BBC maximizes the power transfer capability or decelerating area by operating the shunt FACTS devices at full capacitive rating. However, it is found in this study that, the speed based

BBC is unable to utilize the entire decelerating area in improving the first swing stability limit. In fact, the use of last portion of decelerating area causes chattering action and that may eventually lead to instability. Such a situation occurs when the fault clearing time approaches the actual critical clearing time. This paper proposes a new control strategy of shunt FACTS devices to improve the first swing stability limit by maximizing the decelerating area and fully utilizing it in counterbalancing the accelerating area. The proposed control strategy is then applied to both SVC and STATCOM placed in a single machine and multimachine systems. The results obtained with the proposed control strategy are also compared with those found with conventional BBC

IN "N. MITHULANANTHAN, C. A. CANIZARES, J. REEVE, AND G. J. ROGERS, "COMPARISON OF PSS, SVC, AND STATCOM CONTROLLERS FOR DAMPING POWER SYSTEM OSCILLATIONS," IEEE TRANS. POWER SYSTEMS, PP. 786-792, 2003." This paper discusses and compares different control techniques for damping undesirable interarea oscillation in power systems by means of power system stabilizers (PSS), static var compensators (SVCs), and shunt static synchronous compensators (STATCOMs). The oscillation problem is analyzed from the point of view of Hope bifurcations, an "extended" eigen analysis to study different controllers, their locations, and the use of various control signals for the effective damping of these oscillations. The comparisons are based on the results obtained for the IEEE 50-machine, 145-bus test system, which is a benchmark for stability analysis. ELECTROMECHANICAL oscillations have been observed in many power systems worldwide [1]–[4]. The oscillations may be local to a single generator or generator plant (local oscillations), or they may involve a number of generators widely separated geographically (interarea oscillations). Local oscillations often occur when a fast exciter is used on the generator, and to stabilize these oscillations, power system stabilizers (PSS) were developed. Interarea oscillations may appear as the systems loading is increased across the weak transmission links in the system which characterize these oscillations [4]. If not controlled, these oscillations may lead to total or partial power interruption [2], [5]. Electromechanical oscillations are generally studied by modal analysis of a linearized system model [2], [6]. However, given the characteristics of this problem, alternative analysis techniques can be developed by using bifurcation theory to effectively identify and control the state variables associated with the oscillatory problem [7]–[10]. Among various types of bifurcations, saddle-node, limit-induced, and Hopf bifurcations have been identified as pertinent to instability in power systems [11]. In saddle-node bifurcations, a singularity of a system Jacobian and/or state matrix results in the disappearance of steady state solutions, whereas, in the case of certain limit-induced bifurcations, the lack of steady state solutions may be associated with system controls reaching limits (e.g., generator reactive power limits); these bifurcations typically induce voltage collapse. On the other hand, Hopf bifurcations describe the onset of an oscillatory problem associated with stable or unstable limit cycles in non-linear systems (e.g., interconnected power system). The availability of flexible ac transmission system (FACTS) controllers [12], such as static var compensators (SVCs), thyristor control series compensators (TCSC), static synchronous compensators (STATCOMs), and unified power flow controller (UPFCs), has led their use to damp interarea oscillations [13]–[15]. Hence, this paper first discusses the use of bifurcation theory for the study of electromechanical oscillation problems, and then compares the application of PSS, SVC, and STATCOM controllers, proposing a new controller placement technique and a methodology to choose the best additional control signals to damp the oscillations. The paper is organized as follows: Section II introduces power system modeling and analysis concepts used throughout this paper; thus, the basic theory behind Hopf bifurcations and the modeling and controls of the PSS, SVC, and STATCOM controllers used are briefly discussed. Oscillation control using SVC and STATCOM controllers, including a new placement technique

IN “A. M. SIMÕES, D. C. SAVELLI, P. C. PELLANDA, N. MARTINS, AND P. APKARIAN, "ROBUST DESIGN OF A TCSC OSCILLATION DAMPING CONTROLLER IN A WEAK 500-KV INTERCONNECTION CONSIDERING MULTIPLE POWER FLOW SCENARIOS AND EXTERNAL DISTURBANCES," IEEE TRANS. POWER SYSTEMS, VOL. 24, PP. 226-236, 2009” —The power oscillation damping (POD) controllers implemented in the two thyristor controlled series compensators of the Brazilian North-South (NS) interconnection, in the year 1999, were solely intended to damp the low-frequency NS oscillation mode. These controllers are still under operation and are derived from the modulus of the active power flow in the NS line that is phase-lagged at the frequency of the NS mode and may experience relatively large excursions generated by exogenous disturbances. This paper utilizes the same 1999 data to compare the performance of a proposed robust POD controller design with those of two conventional designs. A recent robust control synthesis algorithm used in this work is based on a non-smooth optimization technique and has the capability to handle various controller structures, including reduced-order, and to deal with time-domain constraints on both controlled and measured outputs. Moreover, the non-smooth design technique encompasses multiple operating conditions subject to various test signals, hence building a truly time-domain multi-scenarios approach. According to the results discussed hereafter, this is a key advantage in the industrial context of increasing demand for performance and robustness. The described results relate to a large-scale system model used in the feasibility studies for that interconnection T HE interconnection of the North-Northeast and the South-Southeast Brazilian subsystems (called North and South subsystems in this paper) in 1999 caused the emergence of a new poorly-damped, low-frequency (0.17–0.25 Hz) swing mode: the North-South (NS) mode [1]–[4]. Thyristor controlled series compensators (TCSCs) [5]–[8] equipped with power oscillation damping (POD) controllers were installed at the North and South ends of the NS intertie, with the sole objective of damping the NS mode. A cost-effective POD design should yield not only good oscillation damping but also moderate transients in the POD output signal, following exogenous disturbances. Due to the finite equipment ratings, a large POD output signal may cause the TCSC to hit its limits. If the TCSC hits limits at every half cycle of the NS mode, the effective magnitude and phase compensation will differ from the intended values, drastically reducing the POD damping control action. Checking equipment performance for exogenous disturbances, such as generating-unit rejections and the ensuing active power surges, is therefore an integral part of POD controller design. The single machine-infinite bus example in Fig. 1 is used to demonstrate the impact of TCSC limits in reducing the intended damping of the critical mode. This example relates to a 1275-MVA power plant supplying 560 MW through a 500-kmlong transmission line whose parameters are identical to those of the NS intertie. The generator is equipped with fast exciter but no PSS. The electromechanical oscillation damping control is exerted by a POD-equipped TCSC in this line. A single-phase to ground fault is applied to the transmission line for 100 ms, and then removed without line opening. The ensuing transients are simulated considering three different MVAr capacities for the TCSC. It is clear from the nonlinear simulated results that a reduction in the TCSC MVAr capacity causes it to hit limits more severely and for a longer period with detrimental impact to its damping control capability Publications from several sources focused on the stabilization of the NS mode either through retuning of the existing power system stabilizers (PSSs) at the three major Northeast power plants [1], [9] or installation of TCSCs equipped with PODs at the two ends of the NS line [1]–[4], [9], [10]. These two damping control options are currently implemented in the actual system, providing a comfortable level of redundancy of damping sources, but this paper focuses only on the TCSC solution. Previous valuable work on POD modulated by TCSCs is vast, including [11]–[15]. The TCSC at the North end (Imperatriz substation, IZ) was supplied by ABB while the other at the South end (Serra da Mesa substation, SMA) was supplied by Siemens, their PODs being designed according to distinct control philosophies [3], [4]. This paper utilizes the SMA POD for the studies of the proposed POD signal, since it presents slightly greater challenges in its design due to the close proximity of the SMA power station.

The existing POD at the Imperatriz substation (IZ POD) is based on an innovative concept that ensures good performance under exogenous disturbances, requiring, however, the online estimation of the frequency to be damped. The IZ POD requires more complex modeling for the correct assessment of its dynamic performance, under a linear analysis perspective, and will be the object of a future publication.

OVERVIEW

A DISTRIBUTION system suffers from current as well as voltage-related power-quality (PQ) problems, which include poor power factor, distorted source current, and voltage disturbances. *The power system operating voltage which is less than 33KV is called Distribution System.* A DSTATCOM, connected at the point of common coupling (PCC), has been utilized to mitigate both types of PQ problems . When operating in current control mode (CCM), it injects reactive and harmonic components of load currents to make source currents balanced, sinusoidal, and in phase with the PCC voltages. In voltage-control mode (VCM) , the DSTATCOM regulates PCC voltage at a reference value to protect critical loads from voltage disturbances, such as sag, swell, and unbalances. However, the advantages of CCM and VCM can not be achieve simultaneously with one active filter device, since two modes are independent of each other.

In CCM operation, the DSTATCOM cannot compensate for voltage disturbances. Hence, CCM operation of DSTATCOM is not useful under voltage disturbances, which is a major disadvantage of this mode of operation . Traditionally, in VCM operation. The DSTATCOM regulates the PCC voltage at 1.0 p.u. However, a load works satisfactorily for a permissible voltage range. Hence, it is not necessary to regulate the PCC voltage at 1.0 p.u. While maintaining 1.0-p.u. voltage, DSTATCOM compensates for the voltage drop in feeder. For this, the compensator has to supply an additional reactive current which increases the source currents. This increases losses in the voltage source inverter (VSI) and feeder. Another important aspect is the rating of the VSI. Due to increased current injection, the VSI is de-rated in steady-state condition. Consequently, its capability to mitigate deep voltage sag decreases. Also, UPF cannot be achieved when the PCC voltage is 1 p.u. In the literature, so far, the operation of DSTATCOM is not reported where the advantages of both modes are achieved based on load requirements while over coming their demerits.

This paper considers the operation of DSTATCOM in VCM and proposes a control algorithm to obtain the reference load terminal voltage. This algorithm provides the combined advantages of CCM and VCM. The UPF operation at the PCC is achieved at nominal load, where regulation is provided during voltage disturbances.

Also, the reactive and harmonic component of load current is supplied by the compensator at any time of operation. The deadbeat predictive controller is used to generate switching pulses. The control strategy is tested with a three-phase four-wire neutral point clamped distribution system.

1.2 POWER QUALITY

"To supply electric energy to the consumer terminals with least amount of disturbance is called power quality."

1.2.1 HISTORY

In the early days of power transmission in the late 19th century problems like voltage deviation during load changes and power transfer limitation were observed due to reactive power unbalances. Most of the AC loads are consuming reactive power due to presence of reactance. Heavy consumption of reactive power causes poor voltage quality.

FIG 1.2 STATCOM view

Today these Problems have even higher impact on reliable and secure power supply in the world of Globalization and Privatization of electrical systems and energy transfer. The development in fast and reliable semiconductors devices (GTO and IGBT) allowed new power electronic Configurations to be introduced to the tasks of power Transmission and load flow control.

The FACTS devices offer a fast and reliable control over the transmission parameters, i.e. Voltage, line impedance, and phase angle between the sending end voltage and receiving end voltage. On the other hand the custom power is for low voltage distribution, and improving the poor quality and reliability of supply affecting sensitive loads. Custom power devices are very similar to the FACTS. Most widely known custom power devices are DSTATCOM, UPQC, DVR among them DSTATCOM is very well known and can provide cost effective solution for the compensation of reactive power and unbalance loading in distribution system.

Maximum AC loads consumes reactive power, it causes poor power quality in power system. The DSTATCOM is a compensating device which is used to control the flow of reactive power in the distribution systems. The complete background of the compensating devices and power electronic application in compensating devices is presented in this paper and also the compensation using the DSTATCOM modeling is also discussed.

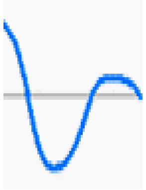
The detailed modeling and simulations of different control strategies are presented and implemented along with the necessary equations in the MATLAB simulink using the sim power systems tool boxes. The PI controllers are used for the implementation of the models and are discussed. Simulation results are we discussed and various case studies applied depending on the various loads like resistive, inductive and capacitive on the DSTATCOM simulink.

1.2.1 List of power quality problems

The most common types of Power Quality problems are presented below along with their description, causes and consequences:

a. *Voltage sag (or dip)*
b. *Very short interruptions*
c. *Long interruptions*
d. *Voltage transients*
e. *Voltage swell*
f. *Harmonic distortion*
g. *Voltage fluctuation*
h. *Noise*
i. *Voltage Unbalance*

a. Voltage sag (or dip)



Voltage

Sag

Description: A decrease of the normal voltage level between **10% and 90%** of the nominal rms voltage at the power frequency, for durations of 0,5 cycle to 1 minute. ***Causes:*** Faults on the transmission or distribution network (most of the times on parallel feeders). Faults in consumer's installation. Connection of heavy loads and start-up of large motors.

Consequences: Malfunction of information technology equipment, namely microprocessor-based control systems (PCs, PLCs, ASDs, etc) that may lead to a process stoppage. Tripping of contactors and electromechanical relays. Disconnection and loss of efficiency in electric rotating machines.

b. Very short interruptions

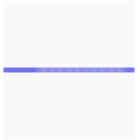
Very short interruptions

Description: Total interruption of electrical supply for duration from few milliseconds to one or two seconds.

Causes: Mainly due to the opening and automatic reclosure of protection devices to decommission a faulty section of the network. The main fault causes are insulation failure, lightning and insulator flashover.

Consequences: Tripping of protection devices, loss of information and malfunction of data processing equipment. Stoppage of sensitive equipment, such as ASDs, PCs, PLCs, if they're not prepared to deal with this situation.

c. Long interruptions



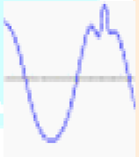
Long interruptions

Description: Total interruption of electrical supply for duration greater than 1 to 2 seconds

Causes: Equipment failure in the power system network, storms and objects (trees, cars, etc) striking lines or poles, fire, human error, bad coordination or failure of protection devices.

Consequences: Stoppage of all equipment.

d. Voltage Transients



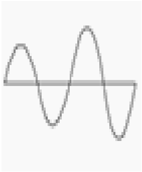
Voltage transient

Description: Very fast variation of the voltage value for durations from a several microseconds to few milliseconds. These variations may reach thousands of volts, even in low voltage.

Causes: Lightning, switching of lines or power factor correction capacitors, disconnection of heavy loads.

Consequences: Destruction of components (particularly electronic components) and of insulation materials, data processing errors or data loss, electromagnetic interference.

e. Voltage swell



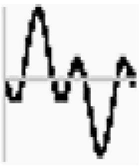
Voltage swell

Description: Momentary increase of the voltage, at the power frequency, outside the normal tolerances, with duration of more than one cycle and typically less than a few seconds.

Causes: Start/stop of heavy loads, badly regulated transformers (mainly during off-peak hours).

Consequences: Data loss, flickering of lighting and screens, stoppage or damage of sensitive equipment, if the voltage values are too high.

f. Harmonic distortion



Harmonic distortion

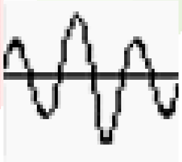
Description: Voltage or current waveforms assume non-sinusoidal shape. The waveform corresponds to the sum of different sine-waves with different magnitude and phase, having frequencies that are multiples of power-system frequency.

Causes: Classic sources: electric machines working above the knee of the magnetization curve (magnetic saturation), arc furnaces, welding machines, rectifiers, and DC brush motors.

Modern sources: all non-linear loads, such as power electronics equipment including ASDs, switched mode power supplies, data processing equipment, high efficiency lighting.

Consequences: Increased probability in occurrence of resonance, neutral overload in 3-phase systems, overheating of all cables and equipment, loss of efficiency in electric machines, electromagnetic interference with communication systems, errors in measures when using average reading meters, nuisance tripping of thermal protections.

g. Voltage fluctuation



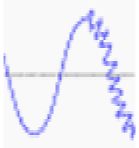
Voltagefluctuation

Description: Oscillation of voltage value, amplitude modulated by a signal with frequency of 0 to 30 Hz.

Causes: Arc furnaces, frequent start/stop of electric motors (for instance elevators), oscillating loads.

Consequences: Most consequences are common to under voltages. The most perceptible consequence is the flickering of lighting and screens, giving the impression of unsteadiness of visual perception.

h. Noise



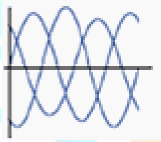
Noise

Description: Superimposing of high frequency signals on the waveform of the power-system frequency.

Causes: Electromagnetic interferences provoked by Hertzian waves such as microwaves, television diffusion, and radiation due to welding machines, arc furnaces, and electronic equipment. Improper grounding may also be a cause.

Consequences: Disturbances on sensitive electronic equipment, usually not destructive. May cause data loss and data processing errors.

i. Voltage Unbalance



Voltage Unbalance

Description: A voltage variation in a three-phase system in which the three voltage magnitudes or the phase angle differences between them are not equal.

Causes: Large single-phase loads (induction furnaces, traction loads), incorrect distribution of all single-phase loads by the three phases of the system (this may be also due to a fault).

Consequences: Unbalanced systems imply the existence of a negative sequence that is harmful to all three- phase loads. The most affected loads are three-phase induction machines.

Power Quality Solutions

Voltage Fluctuations Protecting your power quality is a big business right now. There are many choices of equipment and manufacturers. The most expensive solution is not always the right solution for the problem. Both correct identification of the power problems and your company’s needs should be addressed to ensure an accurate assessment.

Here also is where the use of a qualified power auditor can prove to be invaluable. The auditor will not only identify power quality issues within your company, but will also help you assess your specific needs. The auditor can then put together a recommendation that meets your needs without unnecessary expense.

There are five basic categories of solutions to some of the power quality problems, each having different capabilities, strengths and weaknesses. The following is a list of these categories with links to more information on each one.

Surge Suppressors

Voltage Regulators

Uninterruptable Power Supplies

Generators

FACTS Compensators

Surge suppressors

Transient Voltage Surge Suppression (TVSS) provides protection against transient surges, which can happen so quickly that they do not register on normal electrical testing equipment.

Surge suppressors or surge protectors are the most basic form of power protection. A surge suppressor is often used to shield important, but less critical or highly senstive equipment. It is also used as a complement to more comprehensive power protection solutions. They are passive electronic devices that protect against transient high-level voltages.

Voltage Regulator or Power Conditioner

Many businesses require voltage regulation rather than battery backup power. In those cases where backup power is unnecessary, a voltage regulator can provide superior protection with much higher electrical efficiencies than a UPS.

A voltage regulator may also be referred to by the labels “power conditioner”, “line conditioner”, “voltage stabilizer”, etc. Regardless the term used, these devices are all essentially the same in that they provide voltage regulation and one or more additional power quality-related functions.

Uninterruptable Power Supplies

The Standby UPS consists of a basic battery/power conversion circuit and a switch that senses irregularities in the electric utility. The equipment to be protected is usually directly connected to the primary power source, and the power protection is available only when line voltage dips to the point of creating an outage. Some off-line UPS include surge protection circuits to increase the level of protection they offer.

In the case of power surges, a standby UPS passes the voltage surge to the protected system until it hits a predetermined level, usually around 115% of the input voltage. At the surge limit value, the unit then goes to battery. Although they do provide reasonably good protection against spikes and switching transients. *However, they do not protect against sags, line noise, frequency variation or brownouts unless the battery is delivering power to the protected system.*

1.3Generators

Generators are machines that convert mechanical energy into electrical energy. They are usually used as a backup power source for a facility's critical systems such as elevators and emergency lighting in case of blackout.

However, they do not offer protection against utility power problems such as over voltages and frequency fluctuations, and although most can be equipped with automatic switching mechanisms, the electrical supply is interrupted before switching is completed, so it cannot protect against the damage that blackouts can cause to expensive equipment and machinery.

FACTS Compensators

Facts means flexible alternating current transmission system.

These are recent trend to improve the power quality and power flow problems in a distribution and transmission lines respectively. Detailed about FACTS explained in the next chapter.

1.4 Harmonics

"Harmonics are integer multiples of supply frequency. i.e. 1f, 2f, 3f.....nf.

Where n=harmonic number."

f= supply frequency

`Harmonics are associated with steady-state waveform distortion of currents and voltages Harmonics are components that make up a waveform where each component has a frequency that is an integral multiple of the fundamental frequency.

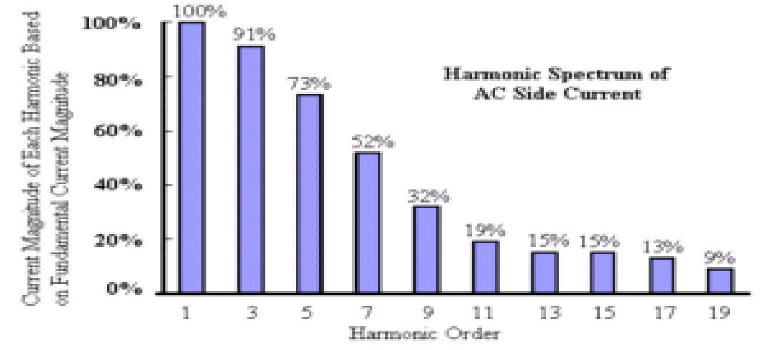


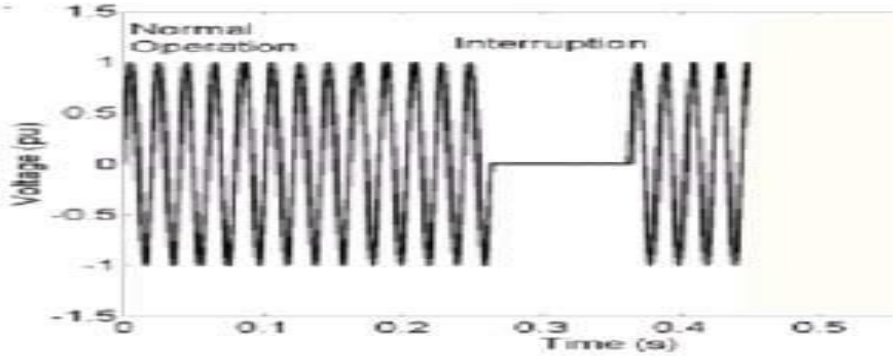
FIG 1.3 Harmonic spectrum of AC side current

The term *Harmonic* is normally applied to waveform components that have frequencies other than the fundamental frequency. For a 50 Hz or 60Hz system the fundamental frequency is 50HZ or 60Hz. A waveform that contains any components other than the fundamental frequency is non-sinusoidal and considered to be *distorted*. Nonlinear loads draw currents that are non-sinusoidal and thus create voltage drops in distribution conductors that are non-sinusoidal.

Typical nonlinear loads include rectifiers, variable speed drives, and any other loads based on solid-state conversion. Transformers and reactors may also become nonlinear elements in a power system during overvoltage conditions. Harmonics create many concerns for utilities and customers alike. Typical phenomena include neutral circuit overloading in three phase circuits, motor and transformer over heating, metering inaccuracies and control system malefactions.

1.5 Interruptions

An Interruption occurs whenever a supply's voltage drops below 10% of the rated voltage for a period of time no longer than one minute. It is differentiated from voltage sag in that the late is not a severe power quality problem. The term sag covers voltage drops down to 10% of nominal voltage whereas an interruption occurs at lower than 10%. A Sustained Interruption occurs when this voltage decrease remains for more than one minute. An interruption is usually caused by downstream faults that are cleared by breakers or fuses. A sustained interruption is caused by upstream breaker or fuse operation.



1.4 interruption waveform

Upstream breakers may operate due to short-circuits, overloads, and loss of stability in the bulk power system. Loss of stability is usually characterized by out-of-tolerance voltage magnitude conditions and frequency variations which exceed electrical machine and transformer tolerances. This phenomenon is often associated with faults and deficiencies in a transmission system but can also be the result of lack of generation resources. The concerns created by interruptions are evident and include inconvenience, loss of production time, loss of product, and loss of service to critical facilities such as hospitals.

1.6 Sags and Swells

*Short duration decrease/increase (sag/swell) in supply voltage***.** A Voltage Sag or Voltage Dig is a decrease in supply voltage of 10% to 90% that lasts in duration from half a cycle to one minute. A Voltage Swell is an increase in supply voltage of 10% to 80% for the same duration.

Voltage sags are one of the most commonly occurring power quality problems. They are usually generated inside a facility but may also be a result of a momentary voltage drop in the distribution supply. *Sags* can be created by sudden but brief changes in load such as transformer and motor inrush and short circuit-type faults. A *sag* may also be created by a step change in load followed by a slow response of a voltage regulator. A voltage *swell* may occur by the reverse of the above events.

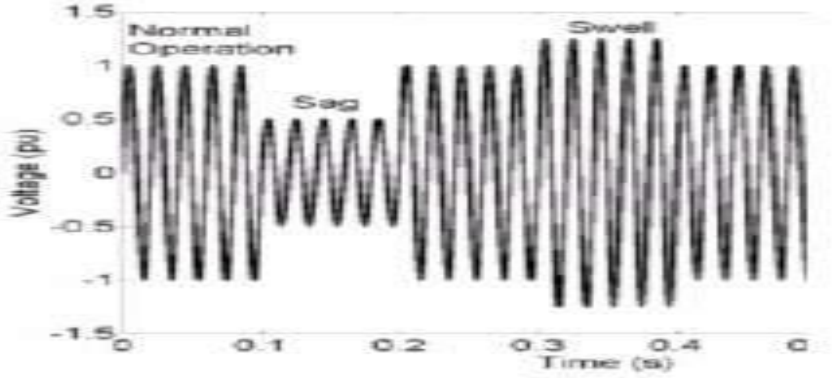


FIG 1.5 Sag and Swell

Electronic equipment is usually the main victim of *sags,* as they do not contain sufficient internal energy to 'ride through' the disturbance. Electric motors tend to suffer less from voltage sags, as motor and load inertias will 'ride through' the sag if it is short enough in duration.

Sags and Swells are mainly appeared in Power system due to Faults and lightings and sudden change of loads...

Disadvantages of power quality

Power quality in the container terminal environment impacts the economics of the terminal operation, affects reliability of the terminal equipment, and affects other consumers served by the same utility service. *Each of these concerns is explained in the following:*

1. Economic Impact: The economic impact of power quality is the foremost incentive to container terminal operators. Economic impact can be significant and manifest itself in several ways:

Power Factor Penalties
System Losses
Power Service Initial Capital Investments

Power Factor Penalties: Many utility companies invoke penalties for low power factor on monthly billings. There is no industry standard followed by utility companies. Methods of metering and calculating power factor penalties vary from one utility company to the next. Some utility companies actually meter kVAR usage and establish a fixed rate times the number of kVAR-hours consumed. Other utility companies monitor kVAR demands and calculate power factor. If the power factor falls below a fixed limit value over a demand period, a penalty is billed in the form of an adjustment to the peak demand charges. A number of utility companies servicing container terminal equipment do not yet invoke power factor penalties.

However, their service contract with the Port may still require that a minimum power factor over a defined demand period be met. The utility company may not continuously monitor power factor or kVAR usage and reflect them in the monthly utility billings; however, they do reserve the right to monitor the Port service at any time.

The average power factor under operating conditions of customer's load at the point where service is metered shall be not less than 85%. If below 85%, the customer may be required to furnish, install and maintain at its expense corrective apparatus which will increase the Power factor of the entire installation to not less than 85%. The customer shall ensure that no excessive harmonics or transients are introduced on to the [utility] system. This may require special power conditioning equipment or filters. The IEEE Std. 519-1992 is used as a guide in Determining appropriate design requirements.'

System Losses: Harmonic currents and low power factor created by nonlinear loads, not only result in possible power factor penalties, but also increase the power losses in the distribution system. These losses are not visible as a separate item on your monthly utility billing, but you pay for them each month. Container cranes are significant contributors to harmonic currents and low power factor. Based on the typical demands of today's high speed container cranes, correction of power factor alone on a typical state of the art quay crane can result in a reduction of system losses that converts to a 6 to 10% reduction in the monthly utility billing. For most of the larger terminals, this is a significant annual saving in the cost of operation.

Power Service Initial Capital Investments: The power distribution system design and installation for new terminals, as well as modification of systems for terminal capacity upgrades, involves high cost, specialized, high and medium voltage equipment. Transformers, switchgear, feeder cables, cable reel trailing cables, collector bars, etc. must be sized based on the kVA demand. Thus cost of the equipment is directly related to the total kVA demand. As the relationship above indicates, kVA demand is inversely proportional to the overall power factor, i.e. a lower power factor demands higher kVA for the same kW load. Container cranes are one of the most significant users of power in the terminal.

Since container cranes with DC, 6 pulse, SCR drives operate at relatively low power factor, the total kVA demand is significantly larger than would be the case if power factor correction equipment were supplied on board each crane or at some common bus location in the terminal. In the absence of power quality corrective equipment, transformers are larger, switchgear current ratings must be higher, feeder cable copper sizes are larger, collector system and cable reel cables must be larger, etc. Consequently, the cost of the initial power distribution system equipment for a system which does not address power quality will most likely be higher than the same system which includes power quality equipment.

2. Equipment Reliability

Poor power quality can affect machine or equipment reliability and reduce the life of components. Harmonics, voltage transients, and voltage system sags and swells are all power quality problems and are all interdependent. Harmonics affect power factor, voltage transients can induce harmonics, the same phenomena which create harmonic current injection in DC SCR variable speed drives are responsible for poor power factor, and dynamically varying power factor of the same drives can create voltage sags and swells. The effects of harmonic distortion, harmonic currents, and line notch ringing can be mitigated using specially designed filters.

3. Power System Adequacy

When considering the installation of additional cranes to an existing power distribution system, a power system analysis should be completed to determine the adequacy of the system to support additional crane loads. Power quality corrective actions may be dictated due to inadequacy of existing power distribution systems to which new or relocated cranes are to be connected. In other words, addition of power quality equipment may render a workable scenario on an existing power distribution system, which would otherwise be inadequate to support additional cranes without high risk of problems.

4. Environment

No issue might be as important as the effect of power quality on our environment. Reduction in system losses and lower demands equate to a reduction in the consumption of our natural nm resources and reduction in power plant emissions. It is our responsibility as occupants of this planet to encourage conservation of our natural resources and support measures which improve our air quality

Reactive Power

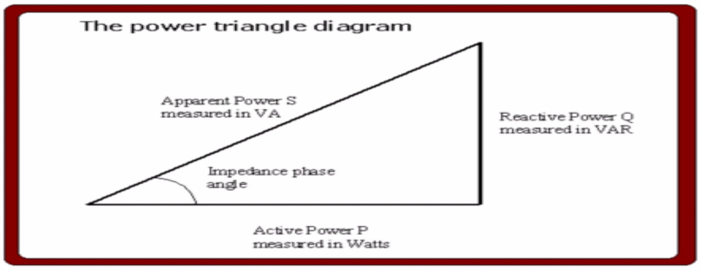


FIG 1.7 Reactive Power

Effects of reactive power on the efficiency of transmission and distribution:

Reactive power is defined as the product of the rms voltage, current, and the sine of the difference in phase angle between the two. It is used to describe the effects of a generator, a load, or other network equipment, which on the average neither supplies nor consumes power. Synchronous generators, overhead lines, underground cables, transformers, loads and compensating devices are the main sources and sinks of reactive power, which either produce or absorb reactive power in the systems. To maintain efficient transmission and distribution, it is necessary to improve the reactive power balance in a system by controlling the production, absorption, and flow of reactive power at all levels in the system. By contrast, inefficient reactive power management can result in high network losses, equipment overloading, unacceptable voltage levels, even voltage instability and outages resulting from voltage collapse. Local reactive power devices for voltage regulation and power factor correction are also important especially for balancing the reactive power demand of large and fluctuating industrial loads.

ACTIVE FILTER

An active filter is a type of analog electronic filter, distinguished by the use of one or more active components i.e. voltage amplifiers or buffer amplifiers. Typically this will be a vacuum tube, or solid-state devices (transistor or operational amplifier). Active filters have three main advantages over passive filters:

- Inductors can be avoided. Passive filters without inductors cannot obtain a high Q (low damping), but with them are often large and expensive (at low frequencies), may have significant internal resistance, and may pick up surrounding electromagnetic signals.

- The shape of the response, the Q (Quality factor), and the tuned frequency can often be set easily by varying resistors, in some filters one parameter can be adjusted without affecting the others. Variable inductances for low frequency filters are not practical.
- The amplifier powering the filter can be used to buffer the filter from the electronic components it drives or is fed from, variations in which could otherwise significantly affect the shape of the frequency response.

Active filter circuit configurations (electronic filter topology) include:

- State variable and biquadrate filters
- Twin T filter (fully passive)
- Dual Amplifier Band pass (DABP)
- Wien notch
- Multiple Feedback Filter

All the varieties of passive filters can also be found in active filters. Some of them are:

- High-pass filters – attenuation of frequencies below their cut-off points.
- Low-pass filters – attenuation of frequencies above their cut-off points.
- Band-pass filters – attenuation of frequencies both above and below those they allow to pass.
- Notch filters – attenuation of certain frequencies while allowing all others to pass.

Combinations are possible, such as notch and high-pass (for example, in a rumble filter where most of the offending rumble comes from a particular frequency), e.g. Elliptic filters.

Design of active filter:

To design filters, the specifications that need to be established include:

- The range of desired frequencies (the passband) together with the shape of the frequency response. This indicates the variety of filter (see above) and the center or corner frequencies.
- Input and output impedance requirements. These limit the circuit topologies available; for example, most, but not all active filter topologies provide a buffered (low impedance) output. However, remember that the internal output impedance of

operational amplifiers, if used, may rise markedly at high frequencies and reduce the attenuation from that expected. Be aware that some high-pass filter topologies present the input with almost a short circuit to high frequencies.

- The degree to which unwanted signals should be rejected.

In the case of narrow-band band pass filters, the Q determines the -3dB bandwidth but also the degree of rejection of frequencies far removed from the center frequency; if these two requirements are in conflict then a staggered-tuning bandpass filter may be needed.

For notch filters, the degree to which unwanted signals at the notch frequency must be rejected determines the accuracy of the components, but not the Q, which is governed by desired steepness of the notch, i.e. the bandwidth around the notch before attenuation becomes small.

For high-pass and low-pass (as well as band-pass filters far from the center frequency), the required rejection may determine the slope of attenuation needed, and thus the "order" of the filter. A second-order all-pole filter gives an ultimate slope of about 12 dB per octave (40dB/decade), but the slope close to the corner frequency is much less, sometimes necessitating a notch be added to the filter.

The allowable "ripple" (variation from a flat response, in decibels) within the *passband* of high-pass and low-pass filters, along with the shape of the frequency response curve near the corner frequency, determine the damping factor (reciprocal of Q). This also affects the phase response, and the time response to a square-wave input.

CHAPTER 2

STRUCTURE OF DSTATCOM AND OPERATION

2.1 INTRODUCTION

Power quality and reliability cost the industry large amounts due to mainly sags and short-term interruptions. Distorted and unwanted voltage wave forms, too. And the main concern for the consumers of electricity was the reliability of supply. Here we define the reliability as the continuity of supply. the problem of distribution lines is divided into two major categories. First group is power quality, second is power reliability. First group consists of harmonic distortions, impulses and swells. Second group consists of voltage sags and outages. Voltage sags is much more serious and can cause a large amount of damage. If exceeds a few cycle, motors, robots, servo drives and machine tools cannot maintain control of process.

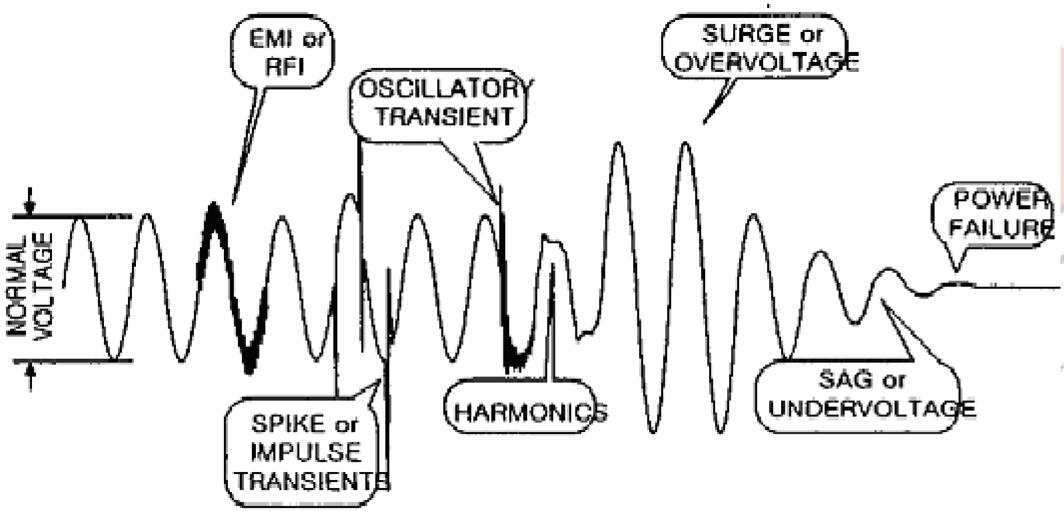


Fig.2.1. power quality and reliability

Both the reliability and quality of supply are equally important. For example, a consumer that is connected to the same bus that supplies a large motor load may have to face a severe dip in his supply voltage every time the motor load is switched on. In some extreme cases even we have to bear the black outs which is not acceptable to the consumers. There are also sensitive loads such as hospitals (life support, operation theatre, and patient database system), processing plants, air traffic control, financial institutions and numerous other data processing and service providers that require clean and uninterrupted power. In processing plants, a batch of product can be ruined by voltage dip of very short duration. Such customers are very wary of such dips since each dip can

cost them a substantial amount of money. Even short dips are sufficient to cause contactors on motor drives
to drop out. Stoppage in a portion of process can destroy the conditions for quality control of product and require restarting of production.

Thus in this scenario in which consumers increasingly demand the quality power, the term power quality (PQ) attains increased significance. Transmission lines are exposed to the forces of nature. Furthermore, each transmission line has its load ability limit that is often determined by either stability constraints or by thermal limits or by the dielectric limits. Even though the power quality problem is distribution side problem, transmission lines are often having an impact on the quality of the power supplied. It is however to be noted that while most problems associated with the transmission systems arise due to the forces of nature or due to the interconnection of power systems, individual customers are responsible for more substantial fraction of the problems of power distribution systems.

2.2 DISTRIBUTED STATIC COMPENSATOR

In 1999 the first SVC with Voltage Source Converter called STATCOM (Static compensator) went into operation. The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs. A STATCOM is build with Thyristors with turn-off capability like GTO or today IGCT or with more and more IGBTs. The static line between the current limitations has a certain steepness determining the control characteristic for the voltage.

The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point. This can be seen in the diagram for the maximum currents being independent of the voltage in comparison to the SVC. This means, that even during most severe contingencies, the STATCOM keeps its full capability.

In the distributed energy sector the usage of Voltage Source Converters for grid interconnection is common practice today. The next step in STATCOM development is the combination with energy storages on the DC-side. The performance for power quality and balanced network operation can be improved much more with the combination of active and reactive power.

The Distribution Static Compensator (DSTATCOM) is a voltage source inverter based static compensator (similar in many respects to the DVR) that is used for the correction of bus voltage sags. Connection (shunt) to the distribution network is via a standard power distribution transformer. The DSTATCOM is capable of generating continuously variable inductive or capacitive shunt compensation at a level up its maximum MVA rating. The DSTATCOM continuously checks the line waveform with respect to a reference ac signal, and therefore, it can provide the correct amount of leading or lagging reactive current compensation to reduce the amount of voltage fluctuations. The major components of a DSTATCOM are shown in Fig. 2. It consists of a dc capacitor, one or more inverter modules, an ac filter, a transformer to match the inverter output to the line voltage, and a PWM control strategy. In this DSTATCOM implementation, a voltage-source inverter converts a dc voltage into a three-phase ac voltage that is synchronized with, and connected to, the ac line through a small tie reactor and capacitor (ac filter).

2.2.1 CIRCUIT DIAGRAM OF DSTATCOM

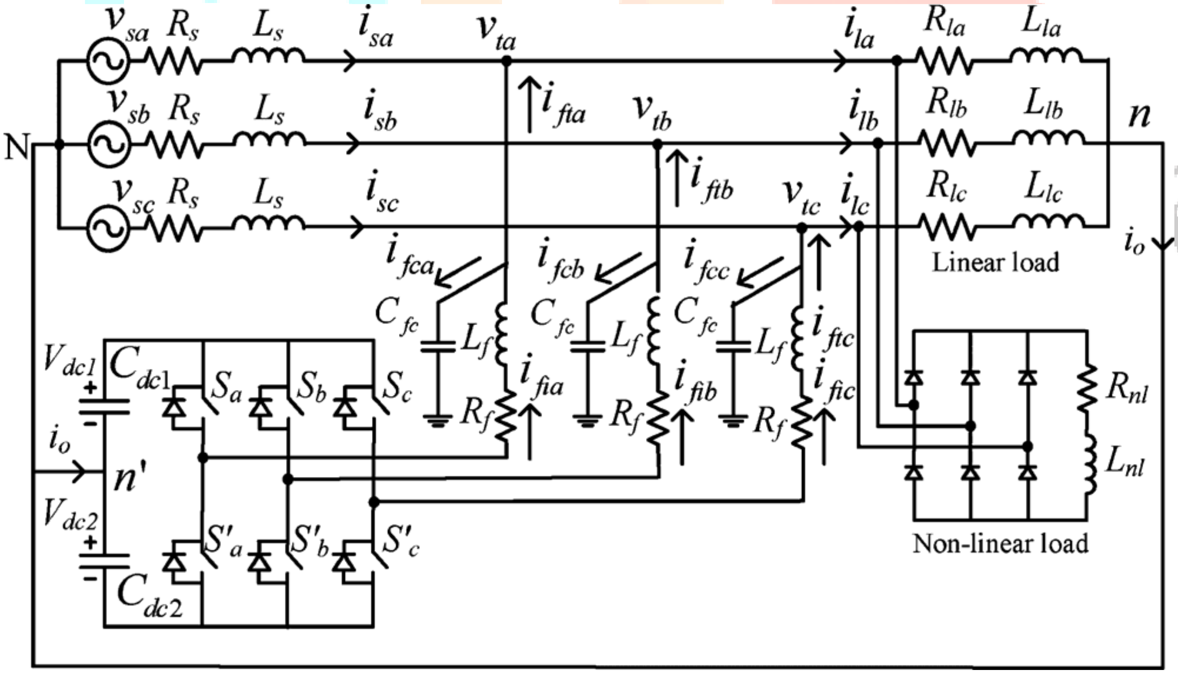


Fig.2.2 Circuit diagram of the DSTATCOM-compensated distribution system

Circuit diagram of a DSTATCOM-compensated distribution system is shown in Fig. 2.2. It uses a three-phase, four-wire, two-level, neutral-point-clamped VSI. This structure allows independent control to each leg of the VSI . Fig.1.2 shows the single-phase equivalent representation of Fig. 1.2. Variable is a switching function, and can be either +1 or 1 depending upon switching state. Filter inductance and resistance are Lf and Rf , respectively. Shunt capacitor eliminates high-switching frequency components.

First, discrete modeling of the system is presented to obtain a discrete voltage control law, and it is shown that the PCC voltage can be regulated to the desired value with properly chosen parameters of the VSI. Then, a procedure to design VSI parameters is presented. A proportional-integral (PI) controller is used to regulate the dc capacitor voltage at a reference value. Based on instantaneous symmetrical component theory and complex Fourier transform, a reference voltage magnitude generation scheme is proposed that provides the advantages of CCM at nominal load.

2.3 DSTATCOM components

DSTATCOM involves mainly three parts

2.3.1 IGBT or GTO based dc-to-ac inverters

These inverters are used which create an output voltage wave that's controlled in magnitude and phase angle to produce either leading or lagging reactive current, depending on the compensation required.

2.3.2 L-C filter

The LC filter is used which reduces harmonics and matches inverter output impedance to enable multiple parallel inverters to share current. The LC filter is chosen in accordance with the type of the system and the harmonics present at the output of the inverter.

2.3.3 Control block

Control block is used which switch Pure Wave DSTATCOM modules as required. They can control external devices such as mechanically switched capacitor banks too. These control blocks are designed based on the various control theories and algorithms like instantaneous PQ theory, synchronous frame theory etc.

2.4 BASIC OPERATING PRINCIPLE

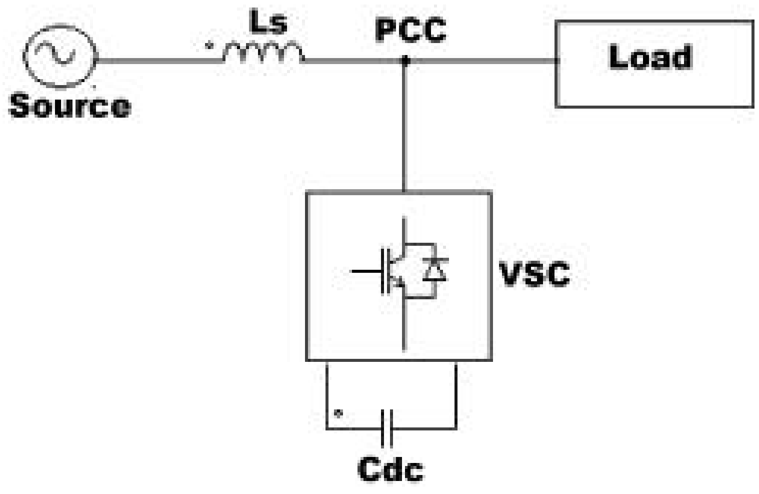


FIG 2.3 Basic structure of DSTATCOM

A DSTATCOM is a controlled reactive source, which includes a Voltage Source Converter (VSC) and a DC link capacitor connected in shunt, capable of generating and/or absorbing reactive power. The operating principles of a DSTATCOM are based on the exact equivalence of the conventional rotating synchronous compensator.

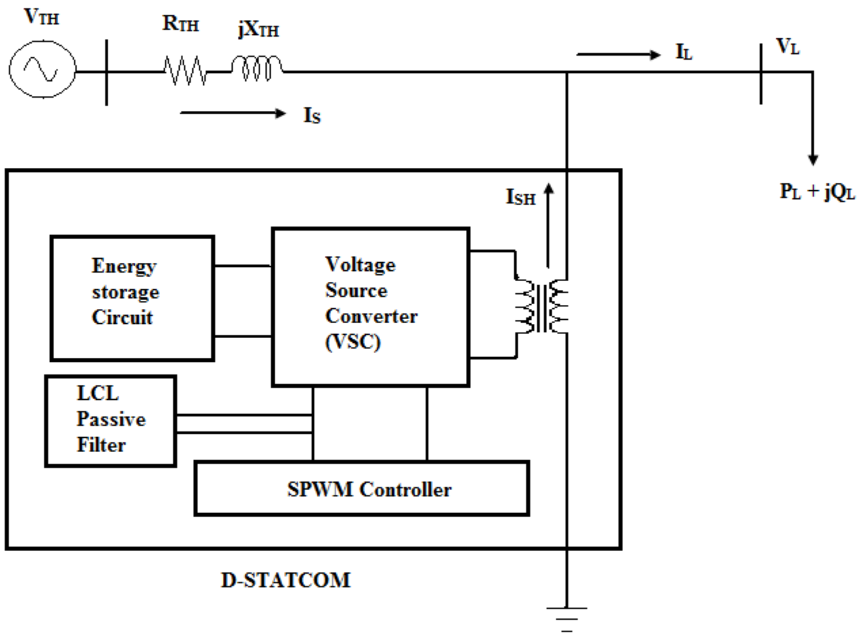


Fig 2.4 Schematic diagram of a D-STATCOM

The D-STATCOM has been utilized mainly for regulation of voltage, correction of power factor and elimination of current harmonics. Such a device is employed to provide continuous voltage regulation using an indirectly controlled converter. In this paper, the DSTATCOM is used to regulate the voltage at the point of connection. The control is based on sinusoidal PWM and only requires the measurement of the rms voltage at the load point.

Basic operating principle of a DSATCOM is similar to that of synchronous machine. The synchronous machine will provide lagging current when under excited and leading current when over excited. DSTATCOM can generate and absorb reactive power similar to that of synchronous machine and it can also exchange real power if provided with an external device DC source.

2.4.1 Exchange of reactive power

If the output voltage of the voltage source converter is greater than the system voltage then the DSATCOM will act as capacitor and generate reactive power (i.e. provide lagging current to the system).

2.4.2 Exchange of real power

As the switching devices are not losses less there is a need for the DC capacitor to provide the required real power to the switches. Hence there is a need for real power exchange with an AC system to make the capacitor voltage constant in case of direct voltage control. There is also a real power exchange with the AC system if DSTATCOM id provided with an external DC source to regulate the voltage in case of very low voltage in the distribution system or in case of faults. And if the VSC output voltage leads the system voltage then the real power from the capacitor or the DC source will be supplied to the AC system to regulate the system voltage to the =1p.u or to make the capacitor voltage constant. Hence the exchange of real power and reactive power of the voltage source converter with AC system is the major required phenomenon for the regulation in the transmission as well as in the distribution system. For reactive power compensation, DSTATCOM provides reactive power as needed by the load and therefore the source current remains at unity power factor (UPF). Since only real power is being supplied by the source, load balancing is achieved by making the source reference current balanced. The reference source current used to decide the switching of the DSTATCOM has real fundamental frequency component of load current which is being extracted by these techniques.

A STATCOM at the transmission level handles only fundamental reactive power and provides voltage support as a DSTATCOM is employed at the distribution level or at the load end for power factor improvement and voltage regulation. DSTATCOM can be one of the viable alternatives to SVC in a distribution network. Additionally, DSTATCOM can also behave as a shunt active filter, to eliminate unbalance or distortions in the source current or the supply voltage. Since a DSTATCOM is such a multifunctional device, the main objective of any control algorithm should be to make it flexible and easy to implement in addition to exploiting its multi functionality to the maximum. The main objective of any compensation scheme is that it should have a fast response, flexible and easy to implement.

The control algorithms of a DSTATCOM are mainly implemented in the following steps:

- Measurements of system voltages and current and
- Signal conditioning
- Calculation of compensating signals
- Generation of firing angles of switching devices

Generation of proper PWM firing is the most important part of DSTATCOM control and has a great impact on the compensation objectives, transient as well as steady state performance. Since a DSTATCOM shares many concepts to that of a STATCOM at transmission level, a few control algorithms have been directly implemented to a DSTATCOM, incorporating Pulse Width Modulation (PWM) switching, rather than Fundamental Frequency switching (FFS) methods. This project makes attempt to compare the following schemes of a DSTATCOM for reactive power compensation and power factor correction based on:

- Phase Shift Control
- Decoupled Current Control (p-q theory)
- Regulation of ac bus and dc link voltage
- Synchronous Reference Frame (SRF) Method

The performance of DSTATCOM with different control schemes have been tested through digital simulations with the different system parameters. The switch on time of the DSTATCOM and the load change time are also mentioned.

2.5 Topology of the power system with DSTATCOM

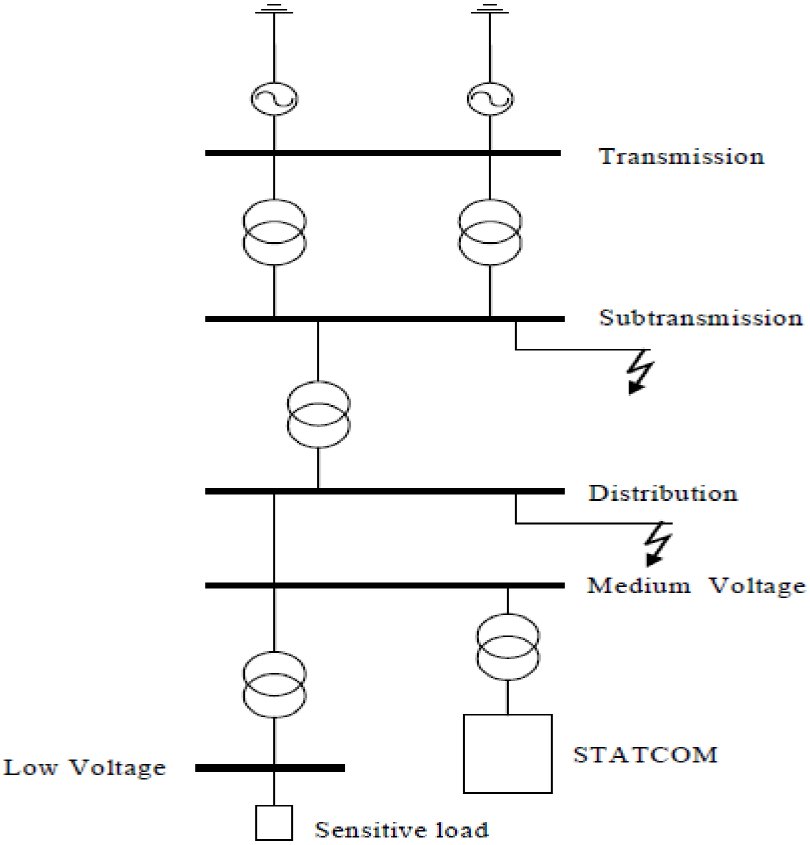


FIG 2.5 Topology of the power system with DSTATCOM

The contribution of the DSTATCOM to the load bus voltage equals the injected current times the impedance seen from the device, which is the source impedance in parallel with the load impedance. The ability of the DSTATCOM to compensate the voltage dip is limited by this available parallel impedance. DSTATCOM is utilized to eliminate the harmonics from the source currents and also balance them in addition to providing reactive power compensation. It helps to reduce the voltage fluctuations at the PCC (point of common coupling). Voltage dips can be mitigated by DSTATCOM, which is based on a shunt connected voltage source converter. VSC with pulse-width modulation (PWM) offers fast and reliable control for voltage dips mitigation. The topology of the DSTATCOM connected at distribution level is shown in above Figure.

2.6 Basic inverter structure

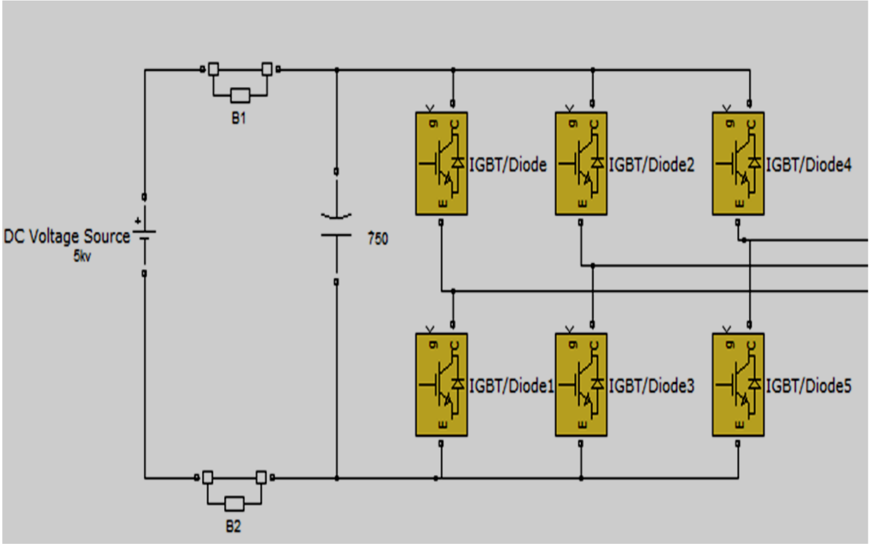


Fig 2.6 Basic inverter structure

The inverter mainly consists of IGBT/Diode, Dc Voltage source or Capacitor. The SIMULINK model representing the compensation using DSTATCOM of a distribution network with induction furnace load is investigated in this work. The SIMULINK model of induction furnace load. Load current is sensed and passed through a sequence analyzer. The magnitude of load current is compared with reference current. Pulse width modulated (PWM) control technique is applied for inverter switching so as to produce a three phase 50 Hz sinusoidal current through the load terminals. Chopping frequency is kept in the range of a few KHz. PI controller is used with the IGBT inverter.

Three-phase inverters are used for variable-frequency drive applications and for high power applications such as HVDC power transmission. A basic three-phase inverter consists of three single-phase inverter switches each connected to one of the three load terminals. For the most basic control scheme, the operation of the three switches is coordinated so that one switch operates at each 60 degree point of the fundamental output waveform. This creates a line-to-line output waveform that has six steps. The six-step waveform has a zero-voltage step between the positive and negative sections of the square-wave such that the harmonics that are multiples of three are eliminated as described above. When carrier-based PWM techniques are applied to six-step waveforms, the basic overall shape.

IMPLEMENTATION

CONCEPT OF PV-STATCOM

Fig. 1 shows the typical real power output of a PV solar farm P during a sunny day and the remaining reactive power capacity Q during a 24-hour period for that day. The proposed smart inverter PV-STATCOM has two modes of operation illustrated in Fig. 1, which are described below:

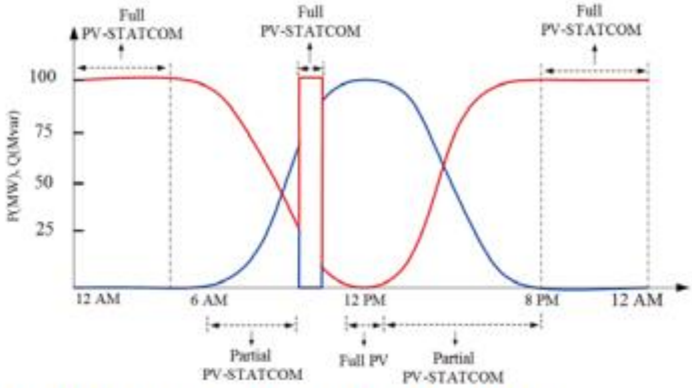


Fig. 1. PV Real and Reactive power during 24 hours on a sunny day

Partial PV-STATCOM mode in this mode, the PV inverter capacity remaining after real power generation is utilized for STATCOM mode of operation. This mode is available during daytime.

Full PV-STATCOM mode in this mode, the entire PV solar farm inverter capacity is made available for STATCOM mode of operation. During daytime, as soon as any unacceptable low-frequency power oscillations due to any system disturbance are detected, the real power generation function is discontinued. The solar inverter is then transformed into a STATCOM with the entire inverter capacity made available for reactive power modulation. Depending upon the system need, reactive power up to the entire inverter capacity can be utilized for power oscillation damping. Once the low-frequency oscillations are damped, the real power generation function is reinstated. The solar farm then ramps up its real power output to the pre-disturbance level while continuing to perform POD in the Partial PV-STATCOM mode. During nighttime, the Full-STATCOM mode is available continuously for POD with reactive power modulation utilizing the entire inverter capacity. The solar farm has another operating mode termed Full PV mode, in which it generates real power based on available irradiance at unity power factor with no smart functions

MODELING OF STUDY SYSTEMS

STUDY SYSTEM 1: SINGLE MACHINE INFINITE BUS (SMIB) System Fig. 2 illustrates the single line diagram of the large synchronous generator connected to an infinite bus through a 600 km line [25]. A 100 MW PV solar farm connected at the mid-point of the transmission line.

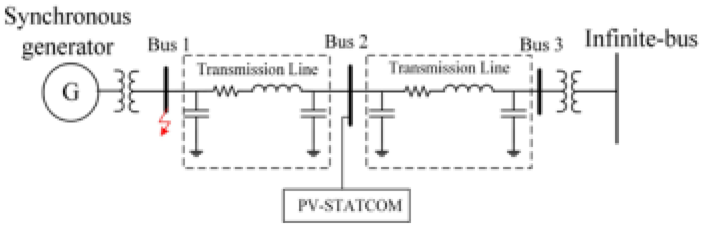


Fig. 2. Single-line diagram of an SMIB system with a 100 MW PV plant connected midline.

STUDY SYSTEM 2: TWO-AREA FOUR MACHINE SYSTEM The Two-Area system having four generators connected with the 220 km tie-line [1] is depicted in Fig. 3. A 100 MW PV system is connected at the midpoint of the tie-line between buses 7 and 9. In both study systems, the synchronous generators are represented by their detailed sixth-order model and DC1-A-type exciter [1]. No Power System Stabilizer (PSS) are installed on generators. The parameters for SMIB system and the Two-Area system are provided in [1] and [25], respectively. The Two-Area system exhibits both local inertial mode and inter-area mode of oscillations in the power flow [1].

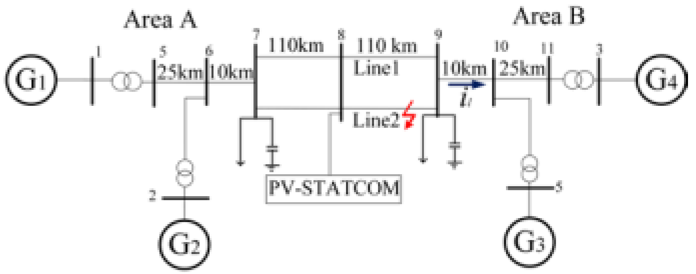


Fig. 3. Single-line diagram of Two-Area system with 100 MW PV plant connected midline.

STUDY SYSTEM 3: 12 BUS FACTS POWER SYSTEM The 12 bus FACTS power system widely is used for studying the impact of FACTS controls [30, 31]. To demonstrate the effectiveness of the proposed controller, POD studies with PV-STATCOM are performed on the 12 bus FACTS power system having multiple oscillatory modes. In this study, no PSSs are considered on generators.

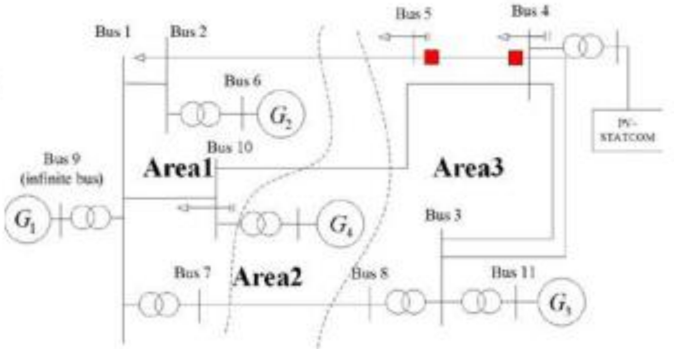


Fig. 4. 12 bus FACTS power system with 100 MW PV solar system at bus 4

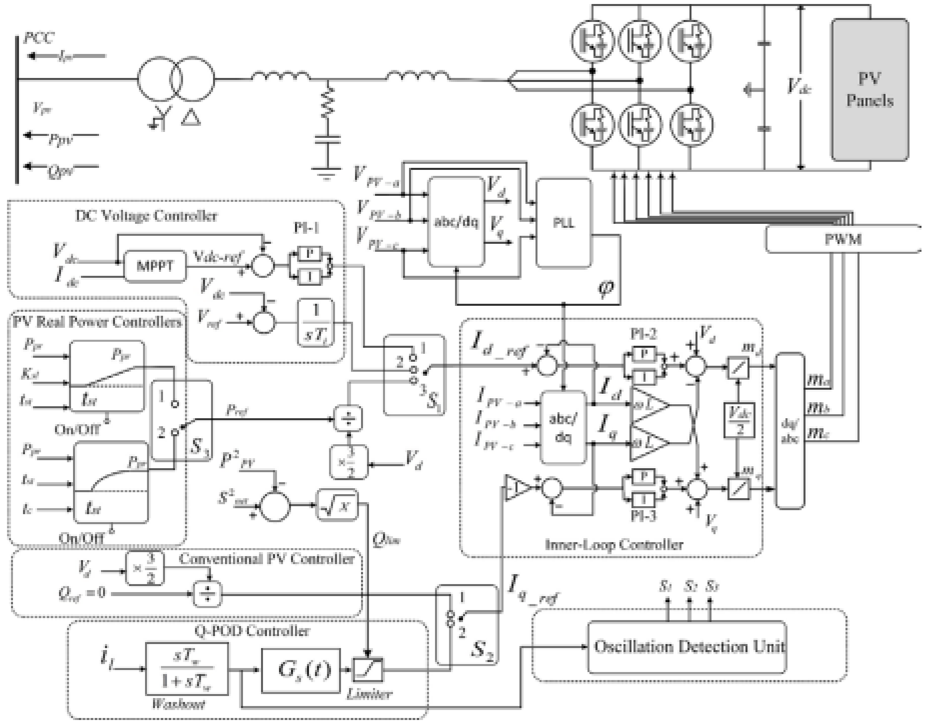


Fig. 5. PV-STATCOM controller

MODELING OF PV-STATCOM

Fig. 5 portrays the different components of the PV system and the PV-STATCOM controller, which are described below. PV Panels and Inverter: The aggregated PV panels are represented by an equivalent panel model which generates PV dc current based on the V-I characteristic of the PV panels [32]. The aggregated solar farm inverter is considered to be of three-phase six-pulse configuration with a DC link capacitor [33]. The PV inverter is connected to the grid through an LCL filter designed based on [34]. The symbols Vpv, Qpv, Ppv, Ipv represent the voltage, inverter reactive power, inverter real power and inverter current at the PCC, respectively. Inner Loop Controller The inner loop controller provides decoupled d-q axis control of real and reactive power based on the d axis reference current Id_ref and q axis reference current Iq_ref, respectively [33]. This controller provides the modulation indices md and mq which are transformed in the dq/abc block to the three phase modulation indices ma, mb, mc. These are used for generating inverter triggering pulses using Pulse Width Modulation (PWM) [31]. The abc to dq transformation unit and Phase Locked Loop (PLL) unit are designed based on [33]. In Fig. 5, Vdc denotes the PV-STATCOM DC link voltage while Vd, Id, Vq, Iq represent the direct and quadrature voltages and currents of PV system, respectively. DC Voltage Controller the DC voltage controller has two components: i) the Maximum Power Point Tracking (MPPT) block with a PI controller, and ii) a DC voltage controller [35]. During conventional PV operating mode, based on the VI characteristic of the PV panels, the MPPT block utilizes Vdc and Idc to generate the reference voltage Vdc-ref, which eventually produces Id_ref for the inner-loop controller. In STATCOM control mode, S1 changes to position 2 and the DC voltage Vdc is regulated to PV panel open circuit voltage to disable real power injection from the PV solar panels [36]. The open-circuit voltage is not a constant and depends on the incident irradiance and temperature. For the specifically utilized PV panel in the solar farm, the largest open circuit voltage obtained from various (manufacturer supplied) power-voltage characteristics for different realistically prevalent temperatures and solar irradiance [32] is chosen as Vref for the DC link voltage controller module in Fig. 5. Conventional PV controller the conventional PV controller regulates the inverter reactive power such that PV power output is at unity power factor [33]. This controller has been adopted from [33], [35], [37] and is utilized only during normal operation of the power system in which unity power factor is required for PV systems. In this control, Q is set to zero during steady state operation resulting in Iq_ref = 0. It is clarified that this controller is deactivated during disturbances, i.e. during power oscillations. In this situation, Iq_ref is generated with the Q-POD controller in a closed loop manner Q-POD Controller The Q-POD controller controls the reactive power output of PV-STATCOM to damp the low-frequency electromechanical oscillations. In this paper, the magnitude of the line current at the PCC of solar farm is selected as the control signal for POD [20]. In Study System 1, il represents the midline current where the PV system is connected. Meanwhile, in Study System 2, il represents the line current between buses 9 and 10. The il signal is fed to the washout filter [34] to remove its steady state component

CONTROL SCHEME

Circuit diagram of a DSTATCOM-compensated distribution system is shown in Fig. 1. It uses a three-phase, four-wire, two-level, neutral-point-clamped VSI. This structure allows independent control to each leg of the VSI [7]. Fig. 2 shows the single-phase equivalent representation of Fig. 1. Variable is a switching function, and can be either *+1* or *-1* depending upon switching state. Filter inductance L_f and resistance R_f are and, respectively. Shunt capacitor

C_{fc} eliminates high-switching frequency components.

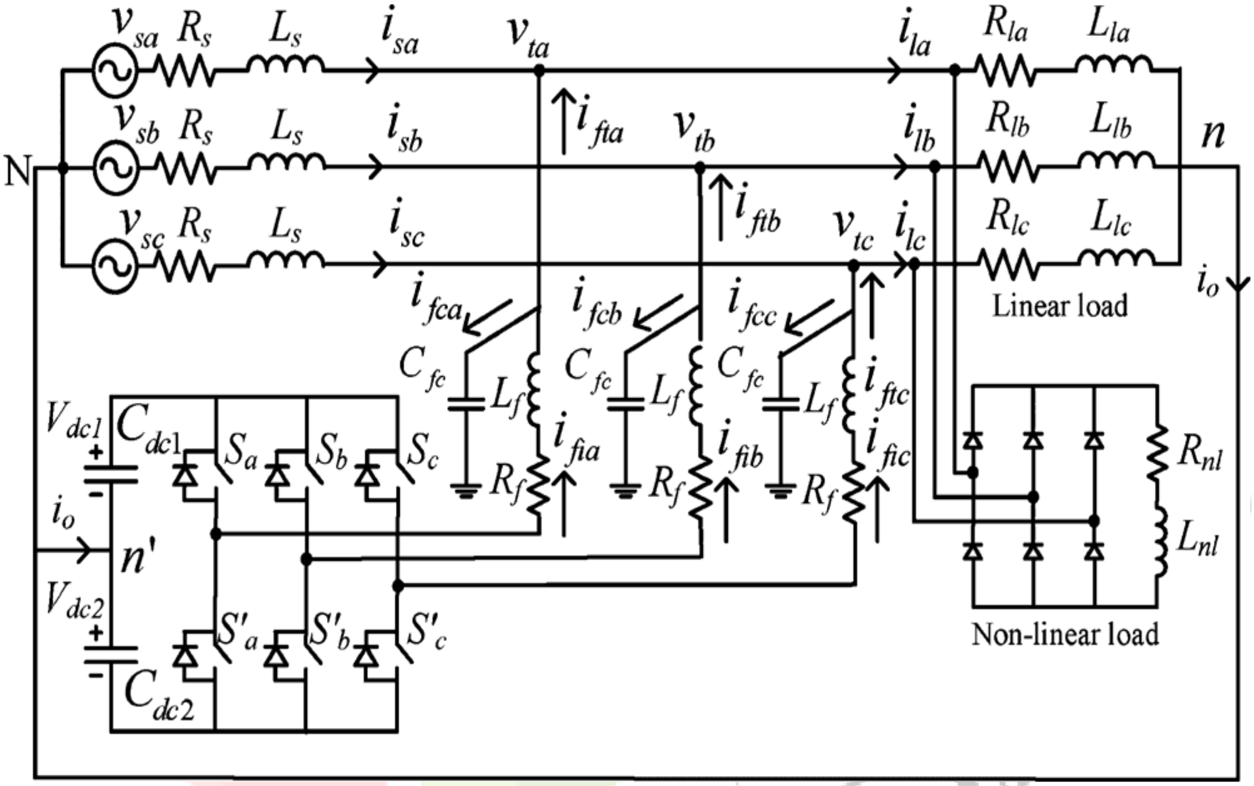


Fig. 1. Circuit diagram of the DSTATCOM-compensated distribution system.

Types of Controllers:

Proportional Controller

A proportional control system is a type of linear feedback controlsystem. In the proportional control algorithm, the controller output is proportional to the error signal, which is the difference between the set point and the process variable . In other words, the output of a proportional controller is the multiplication product of the error signal and the proportional gain. Proportional controller is used to improve the stability. But the steady state error increased.

This can be mathematically expressed as

$$P_{out} = K_p\, e(t) + p_0$$

p_0: Controller output with zero error.
P_{out}: Output of the proportional controller
K_p: Proportional gain
$e(t)$: error

Proportional- Integral controller:

The general block diagram of the PI speed controller is shown in Figure 2

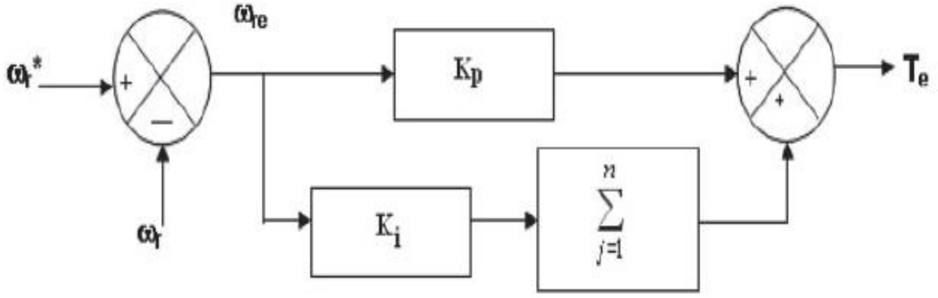


FIG. 2. Block diagram of PI speed controller.

Fig

The output Of the speed controller (torque command) at *n*-th instant is expressed as follows:

$$Te\,(n) = Te(n-1) + Kp\_\omega re(n) + Ki\omega re(n) \quad (10)$$

Where *Te* (*n*) is the torque output of the controller at the *n*-th instant, and K_p and K_i the proportional and integral gain constants, respectively.

A limit of the torque command is imposed as

$$T_{e(n+1)} = \begin{cases} T_{e\max} & \text{for} \quad T_{e(n+1)} \geq T_{e\max} \\ -T_{e\max} & \text{for} \quad T_{e(n+1)} \leq -T_{e\max} \end{cases}$$

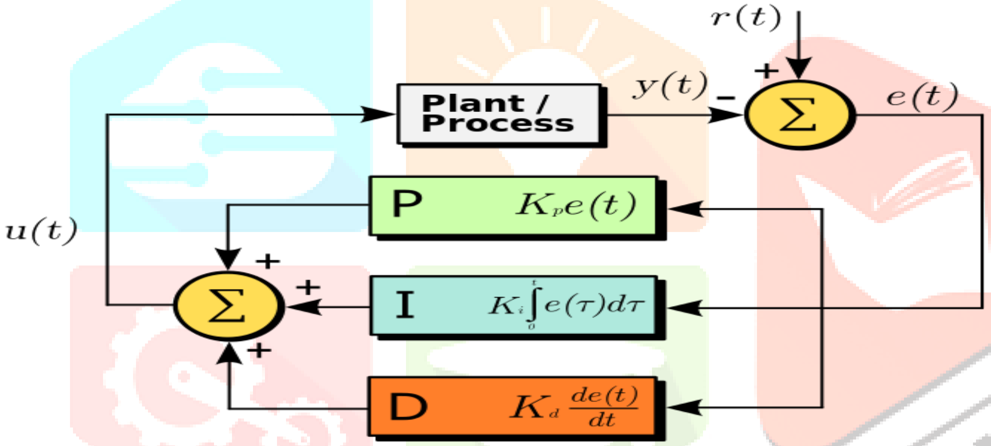
The gains of PI controller shown in (10) can be selected by many methods such as trial and error method, Ziegler–Nichols method and evolutionary techniques-based searching. The numerical values of these controller gains depend on the ratings of the motor.

Proportional and Integral controller is used to reduce the steady sate error of the system, but the pole number increase stability effected.

Advantages and disadvantages

- The integral term in a PI controller causes the steady-state error to reduce to zero, which is not the case for proportional-only control in general.
- The lack of derivative action may make the system more steady in the steady state in the case of noisy data. This is because derivative action is more sensitive to higher-frequency terms in the inputs.
- Without derivative action, a PI-controlled system is less responsive to real (non-noise) and relatively fast alterations in state and so the system will be slower to reach setpoint and slower to respond to perturbations than a well-tuned PID system may be.

Proportional-Integral-Derivative controller:



A proportional-integral-derivative controller (PID controller) is a control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an *error* value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the *error* by adjusting the process through use of a manipulated variable.

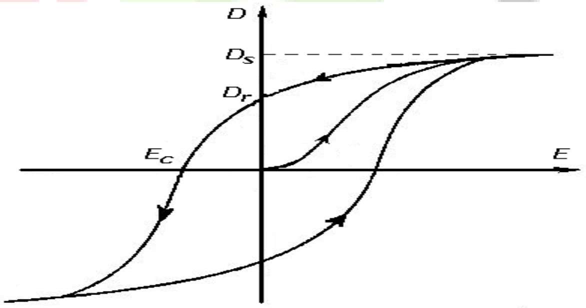
The PID controller algorithm involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted *P, I,* and *D*. Simply put, these values can be interpreted in terms of time: *P* depends on the present error, *I* on the accumulation of past errors, and *D* is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, a damper, or the power supplied to a heating element. For a discrete time case, the term PSD, for proportional-summation-derivative, is often used

Hysteresis Controllers:

Hysteresis is the time-based dependence of a system's output on current and past inputs. The dependence arises because the history affects the value of an internal state. To predict its future outputs, either its internal state or its history must be known.[1] If a given input alternately increases and decreases, a typical mark of hysteresis is that the output forms a loop as in the figure.

Such loops may occur purely because of a dynamic lag between input and output. This effect disappears as the input changes more slowly. This effect meets the description of hysteresis given above, but is often referred to as rate-dependent hysteresis to distinguish it from hysteresis with a more durable memory effect.

Hysteresis occurs in ferromagnetic materials and ferroelectric materials, as well as in the deformation of some materials (such as rubber bands and shape-memory alloys in response to a varying force. In natural systems hysteresis is often associated with irreversible thermodynamic change. Many artificial systems are designed to have hysteresis: for example, in thermostats and Schmitt triggers, the principle of hysteresis is applied to avoid unwanted rapid switching. Hysteresis has been identified in many other fields, including economics and biology.



First, discrete modeling of the system is presented to obtain a discrete voltage control law, and it is shown that the PCC voltage can be regulated to the desired value with properly chosen parameters of the VSI. Then, a procedure to design VSI parameters is presented. A proportional-integral (PI) controller is used to regulate the dc capacitor voltage at a reference value. Based on instantaneous symmetrical component theory and complex Fourier transform, a reference voltage magnitude generation scheme is proposed that provides the advantages of CCM at nominal load. The overall controller block diagram is shown in Fig. 3. These steps are explained as follows.

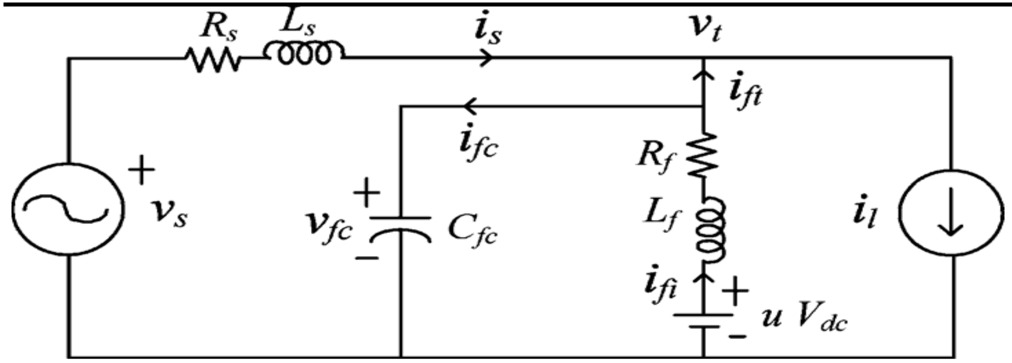


Fig. 2. Single-phase equivalent circuit of DSTATCOM

A. System Modeling and Generation of the Voltage-Control Law

The state-space equations for the circuit shown in Fig. 2 are given by

$$\dot{x} = A\,x + B\,z \qquad (1)$$

Where

$$A = \begin{bmatrix} 0 & \frac{1}{C_{fc}} & 0 \\ -\frac{1}{L_f} & -\frac{R_f}{L_f} & 0 \\ -\frac{1}{L_s} & 0 & -\frac{R_s}{L_s} \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & -\frac{1}{C_{fc}} & 0 \\ \frac{V_{dc}}{L_f} & 0 & 0 \\ 0 & 0 & \frac{1}{L_s} \end{bmatrix},$$

$$x = [v_{fc} \quad i_{fi} \quad i_s]^t, \quad z = [u \quad i_{ft} \quad v_s]^t.$$

The general time-domain solution of (1) to compute the state vector *x(t)*with known initial value *x(t_0)*, is given as follows:

$$x(t) = e^{A(t-t_0)}\,x(t_0) + \int_{t_0}^{t} e^{A(t-\tau)} B\,z(\tau)\,d\tau. \qquad (2)$$

The equivalent discrete solution of the continuous state is obtained by replacing $t_0=kT_d$ and

$t= (k+1)T_d$ as follows:

$$x(k+1) = e^{AT_d}\,x(k) + \int_{kT_d}^{T_d+kT_d} e^{A(T_d+kT_d-\tau)} B\,z(\tau)\,d\tau. \qquad (3)$$

In (3), *k* and T_d represent the *kth* sample and sampling period, respectively. During the consecutive sampling period, the value of *Z(T)* is held constant, and can be taken as *Z(k)*. After simplification and changing the integration variable, (3) is written as

$$x(k+1) = e^{AT_d}\,x(k) + \int_{0}^{T_d} e^{A\lambda} B\,d\lambda\,z(k). \qquad (4)$$

Equation (4) is rewritten as follows:

$$x(k+1) = G\,x(k) + H\,z(k) \qquad (5)$$

Where *G* and *H* are sampled matrices, with a sampling time of T_d.

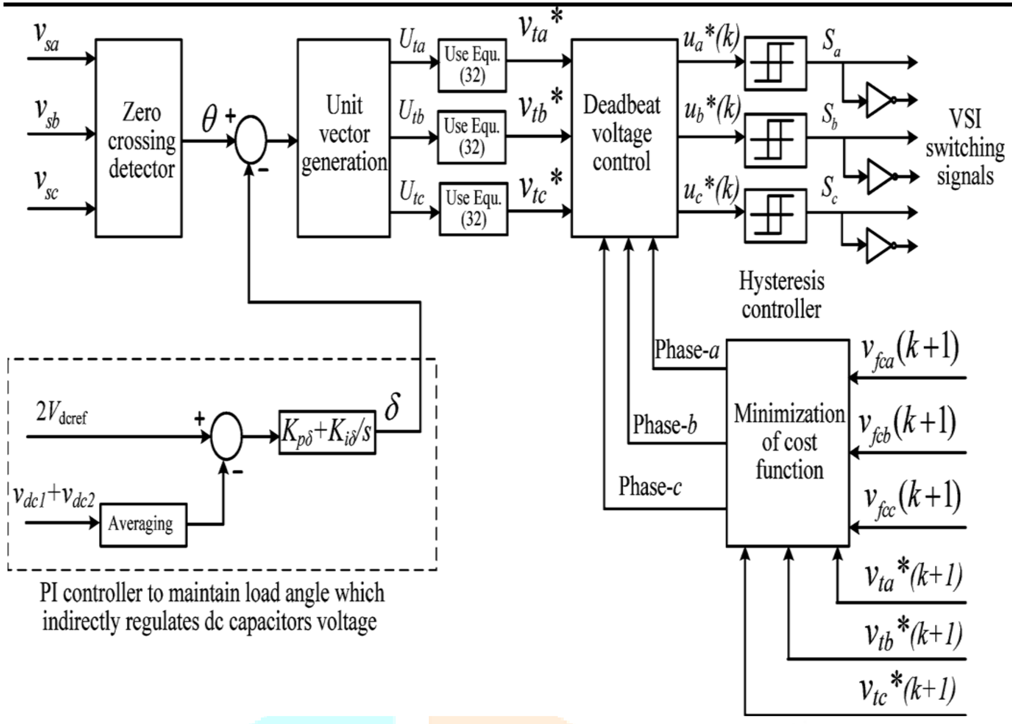


Fig. 3. Overall block diagram of the controller to control DSTATCOM in a distribution system

For small sampling time T_d, matrices G and H are calculated as follows:

$$G = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} = e^{AT_d} \approx I + AT_d + \frac{A^2T_d^2}{2} \quad (6)$$

$$H = \begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{21} & H_{22} & H_{23} \\ H_{31} & H_{32} & H_{33} \end{bmatrix} = \int_0^{T_d} e^{A\lambda} B \, d\lambda$$

$$\approx \int_0^{T_d} (I + A\lambda) \, B \, d\lambda. \quad (7)$$

From (6) and (7), $G11=1-T_d^2/2L_fC_f$, $G_{12}= T_d/C_{fc}-T_d^2R_f/2L_fC_{fc}$, $G_{13}=0$, $H_{11}= T_d^2V_{dc}/2L_fC_{fc}$, $H12= T_d/C_{fc}$ and $H_{13}=0$. Hence, the capacitor voltage using (5) is given as

$$v_{fc}(k+1)=G_{11}v_{fc}(k)+G_{12}i_{fi}(k)+H_{11}u(k)+H_{12}i_{ft}(k). \quad (8)$$

As seen from (8), the terminal voltage can be maintained at a reference value depending upon the VSI parameters V_{dc}, L_f, C_{fc}, R_f, and sampling time T_d. Therefore, VSI parameters must be chosen carefully. Let V_t^* be the reference load terminal voltage.

A cost function is chosen as follows [8]:

$$J = \left[v_{fc}(k+1) - v_t^*(k+1)\right]^2. \quad (9)$$

The cost function is differentiated with respect to *u(k)* and its minimum is obtained at

$$v_{fc}(k+1) = v_t^*(k+1). \quad (10)$$

The deadbeat voltage-control law, from (8) and (10), is given as

$$u^{*}(k) = \frac{v_t^{*}(k+1) - G_{11}v_{fc}(k) - G_{12}i_{fi}(k) - H_{12}i_{ft}(k)}{H_{11}}. \qquad (11)$$

In (11), $V_t^{*}(k+1)$ is the future reference voltage which is unknown. One-step-ahead prediction of this voltage is done using a second-order Lagrange extrapolation formula as follows:

$$v_t^{*}(k+1) = 3\,v_t^{*}(k) - 3\,v_t^{*}(k-1) + v_t^{*}(k-2). \qquad (12)$$

The term $V_t^{*}(k+1)$ is valid for a wide frequency range [17] and when substituted in (11), yields to a one-step-ahead deadbeat voltage-control law. Finally, *u(k)* is converted into the ON/OFF switching command to the corresponding VSI switches using a deadbeat and hysteresis controller [17].

B. Design of VSI Parameters

DSTATCOM regulates terminal voltage satisfactorily, depending upon the properly chosen VSI parameters. The design procedure of these parameters is presented as follows.

1) Voltage across DC Bus (V_{dc}): The dc bus voltage is taken twice the peak of the phase voltage of the source for satisfactory performance [19]. Therefore, for a line voltage of 400 V, the dc bus voltage is maintained at 650 V.

2) DC Capacitance (C_{dc}): Values of dc capacitors are chosen based on a period of sag/swell and change in dc bus voltage during transients. Let the total load rating be ***S*** kVA. In the worst case, the load power may vary from minimum to maximum that is, from 0 to ***S*** kVA. The compensator needs to exchange real power during transient to maintain the load power demand. This transfer of real power during the transient will result in the deviation of capacitor voltage from its reference value. The voltage continues to decrease until the capacitor voltage controller comes into action. Consider that the voltage controller takes ***p*** cycles, that is, ***pT*** seconds to act, where ***T*** is the system time period. Hence, maximum energy exchange by the compensator during transient will be ***pST***. This energy will be equal to the change in the capacitor stored energy. Therefore

$$\frac{1}{2}C_{dc}\left(V_{dcref}^{2} - V_{dc}^{2}\right) = p\,S\,T \qquad (13)$$

Where V_{dcref} and V_{dc} are the reference dc bus voltage and maximum allowed voltage during transients, respectively. Hence

$$C_{dc} = \frac{2pST}{V_{dcref}^{2} - V_{dc}^{2}}. \qquad (14)$$

Here, S=10 kVA, V_{dcref} = 650 V, $p=1$, and $V_{dc}=0.8V_{dcref}$ or $V_{dc}=1.2V_{dc}$. Using (14), capacitor values are found to be 2630μf and 2152 μf. The capacitor value 2600 μf is chosen to achieve satisfactory performance during all operating conditions

3) Filter Inductance (L_f): Filter inductance L_f should provide reasonably high switching frequency and a sufficient rate of change of current such that VSI currents follow desired currents. The following equation represents inductor dynamics:

$$L_f \frac{di_{fi}}{dt} = -v_{fc} - R_f i_{fi} + V_{dc}. \qquad (15)$$

The inductance L_f is designed to provide good tracking performance at a maximum switching frequency (f_{max}) which is achieved at the zero of the source voltage in the hysteresis controller. Neglecting R_f, L_f is given by

$$L_f = \frac{2V_m}{(2h_c)(2f_{\max})} = \frac{0.5V_m}{h_c f_{\max}} \qquad (16)$$

Where $2h_c$ is the ripple in the current. With f_{max} =10 kHz and h_c =0.75 A (5% of rated current), the value of L_f using (16) is found to be 21.8 mH, and 22 mH is used in realizing the filter.

4) Shunt Capacitor (C_{fc}): The shunt capacitor should not resonate with feeder inductance at the fundamental frequency (ω_0). Capacitance, at which resonance will occur, is given as

$$C_{fcr} = \frac{1}{\omega_0^2 L_s}. \qquad (17)$$

For proper operation, C_{fc} must be chosen very small compared to C_{fcr} . Here, a value of 5μf is chosen which provides an impedance of 637Ω at ω_0 . This does not allow the capacitor to draw significant fundamental reactive current.

C. Controller for DC Bus Capacitor Voltage

Average real power balance at the PCC will be

$$P_{pcc} = P_{lavg} + P_{loss} \qquad (18)$$

Where P_{pcc}, P_{lavg}, and P_{loss}, are the average PCC power, load power, and losses in the VSI, respectively. The power available at the PCC, which is taken from the source, depends upon the angle between source and PCC voltages, that is, load angle δ. Hence δ must be maintained constant to keep P_{pcc} constant.

The voltage of the dc bus of DSTATCOM can be maintained at its reference value by taking inverter losses P_{loss} from the source. If the capacitor voltage is regulated to a constant reference value, P_{loss} is a constant value. Consequently, δ is also a constant value. Thus, it is evident that dc-link voltage can be regulated by generating a suitable value of δ. This includes the effect of losses in the VSI and, therefore, it takes care of the term P_{loss} in its action. To calculate load angle, δ the averaged dc-link voltage ($V_{dc1}+V_{dc2}$) is compared with a reference voltage, and error is passed through a PI controller. The output of the PI controller, which is load angle, δ is given as follows:

$$\delta = K_{p\delta}\, e_{\mathrm{vdc}} + K_{i\delta} \int e_{\mathrm{vdc}}\, dt \qquad (19)$$

Where $e_{vdc} = 2V_{dcref}-(V_{dc1}+V_{dc2})$ is the voltage error. Terms $K_{p\delta}$ and $K_{i\delta}$ are proportional and integral gains, respectively. δ must lie between 0 to 90 for the power flow from the source to PCC. Hence, controller gains must be chosen carefully.

D. Proposed Method to Generate Reference Terminal Voltages

Reference terminal voltages are generated such that, at nominal load, all advantages of CCM operation are achieved while DSTATCOM is operating in VCM. Hence, the DSTATCOM will inject reactive and harmonic components of load current. To achieve this, first the fundamental positive-sequence component of load currents is computed. Then, it is assumed that these currents come from the source and considered as reference source currents at nominal load. With these source currents and for UPF at the PCC, the magnitude of the PCC voltage is calculated.

Let three-phase load currents $i_{la}(t)$, $i_{lb}(t)$, $i_{lc}(t)$ and be represented by the following equations:

$$i_{lj}(t) = \sum_{n=1}^{m} \sqrt{2}\, I_{lj\,n} \sin\left(n\,\omega t + \phi_{lj\,n}\right) \qquad (20)$$

Where j= a, b, c represent three phases, n is the harmonic number, and m is the maximum harmonic order. Ø_{lan} Represents the phase angle of the nth harmonic with respect to reference in phase-a and is similar to other phases. Using instantaneous symmetrical component theory, instantaneous zero-sequence $i_{la}^{0}(t)$, positive-sequence $i_{la}^{+}(t)$, and negative-sequence current $i_{la}^{-}(t)$

components are calculated as follows:

$$\begin{bmatrix} i_{la}^{0}(t) \\ i_{la}^{+}(t) \\ i_{la}^{-}(t) \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^{2} \\ 1 & \alpha^{2} & \alpha \end{bmatrix}\begin{bmatrix} i_{la}(t) \\ i_{lb}(t) \\ i_{lc}(t) \end{bmatrix} \qquad (21)$$

Where a is a complex operator and defined by $e^{j2\pi/3}$.

The fundamental positive-sequence component of load current, $I_{la1}^{+}(t)$ calculated by finding the complex Fourier coefficient, is expressed as follows:

$$\bar{I}_{la1}^{+} = \frac{\sqrt{2}}{T}\int_{0}^{T} i_{la}^{+}(t)\, e^{-j(\omega t - 90^{\circ})}\, dt. \qquad (22)$$

$\bar{I}_{la1}^{+}(t)$ is a complex quantity, contains magnitude and phase angle information, and can be expressed in phasor form as follows:

$$\bar{I}_{la1}^{+} = \left|\bar{I}_{la1}^{+}\right| \angle \bar{I}_{la1}^{+}. \qquad (23)$$

Hence, the instantaneous fundamental positive-sequence component of load current $i_{la1}^{+}(t)$ in phase-a, is expressed as

$$i_{la1}^{+}(t) = \sqrt{2}\left|\bar{I}_{la1}^{+}\right| \sin\left(\omega t + \angle \bar{I}_{la1}^{+}\right). \qquad (24)$$

The fundamental positive-sequence component of load currents must be supplied by the source at nominal load. Hence, it will be treated as reference source currents. For UPF at nominal operation, the nominal load angle δ_0 is used. By knowing, fundamental positive-sequence currents $i_{la1}^{+}(t)$ in phases b and c can be easily computed by providing a phase displacement of $2\pi/3$ and $-2\pi/3$, respectively, and are given as

$$\begin{aligned} i_{sa}^{*} &= i_{la1}^{+}(t) = \sqrt{2}\left|\bar{I}_{la1}^{+}\right| \sin\left(\omega t - \delta_0\right) \\ i_{sb}^{*} &= i_{lb1}^{+}(t) = \sqrt{2}\left|\bar{I}_{la1}^{+}\right| \sin\left(\omega t - \frac{2\pi}{3} - \delta_0\right) \\ i_{sc}^{*} &= i_{lc1}^{+}(t) = \sqrt{2}\left|\bar{I}_{la1}^{+}\right| \sin\left(\omega t + \frac{2\pi}{3} - \delta_0\right). \qquad (25) \end{aligned}$$

When reference source currents derived in (25) are supplied by the source, three-phase terminal voltages can be computed using the following equations:

$$v_{tj}(t) = v_{sj}(t) - L_s\frac{di_{sj}^{*}}{dt} - R_s i_{sj}^{*}. \qquad (26)$$

Let the rms value of reference terminal and source voltages be $V_s^{*}$and V^{*}, respectively. For UPF, the source current and terminal voltage will be in phase. However, to obtain the expression of V^* independent of δ_0, we assume the PCC voltage as a reference phasor for the time-being. Hence, phase-a quantities, by considering UPF at the PCC, will be

$$\begin{aligned} v_{ta}(t) &= \sqrt{2}\, V_t^* \sin \omega t \\ i_{sa}^* &= \sqrt{2}\, \left|\bar{I}_{la1}^+\right| \sin \omega t \\ v_{sa}(t) &= \sqrt{2}\, V \sin(\omega t + \delta_0). \end{aligned} \tag{27}$$

Substituting (27) into (26), the phasor equation will be

$$V_t^* \angle 0 = V \angle \delta_0 - (R_s + jX_s)\left|\bar{I}_{la1}^+\right| \angle 0. \tag{28}$$

Simplifying the above equation

$$V_t^* = V \cos \delta_0 + jV \sin \delta_0 - \left|\bar{I}_{la1}^+\right| R_s - j\left|\bar{I}_{la1}^+\right| X_s. \tag{29}$$

Equating real and imaginary parts of both sides of (29), the following equation is obtained:

$$\begin{aligned} V \cos \delta_0 &= V_t^* + \left|\bar{I}_{la1}^+\right| R_s \\ V \sin \delta_0 &= \left|\bar{I}_{la1}^+\right| X_s. \end{aligned} \tag{30}$$

To remove δ_0 from (30), both sides are squared and added to obtain the following:

$$V^2 = \left(V_t^* + \left|\bar{I}_{la1}^+\right| R_s\right)^2 + \left(\left|\bar{I}_{la1}^+\right| X_s\right)^2. \tag{31}$$

After rearranging (31), the expression for reference load voltage magnitude will be

$$V_t^* = \sqrt{V^2 - \left(\left|\bar{I}_{la1}^+\right| X_s\right)^2} - \left|\bar{I}_{la1}^+\right| R_s. \tag{32}$$

Finally, V_t^* using from (32), the load angle from (19), and the phase- a source voltage as reference, three-phase reference terminal voltages are given as

$$\begin{aligned} v_{ta}^*(t) &= \sqrt{2}\, V_t^* \sin(\omega t - \delta) \\ v_{tb}^*(t) &= \sqrt{2}\, V_t^* \sin\left(\omega t - \frac{2\pi}{3} - \delta\right) \\ v_{tc}^*(t) &= \sqrt{2}\, V_t^* \sin\left(\omega t + \frac{2\pi}{3} - \delta\right). \end{aligned} \tag{33}$$

Instantaneous Symmetrical component (p-q theory) theory:

The *dq0* transform (often called the Park's transformation) is a space vector transformation of three-phase time-domain signals from a stationary phase coordinate system (*abc*) to a rotating coordinate system (*dq0*). His is also called rotating reference frame theory.

The transform applied to time-domain voltages in the natural frame (i.e. u_a, u_b and u_c) is as follows:

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

Where $\theta = \omega t + \delta_A$ the angle between the rotating and fixed coordinate system at each is time *t* and δ_A is an initial phase shift of the voltage.

The inverse transformation from the dq0 frame to the natural *abc* frame:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} u_d \\ u_q \\ u_o \end{bmatrix}$$

For example, for voltages u_a, u_b and u_c, the zero sequence components for both the dq0 and symmetrical components transforms is: $\frac{1}{3}(U_a + U_b + U_c)$

The *dq0* transform is essentially an extension of the Clarke transform, applying an angle transformation to convert from a stationary reference frame to a synchronously rotating frame. The synchronous reference frame can be aligned to rotate with the voltage (e.g. used in voltage source converters) or with the current (e.g. used in current source converters).

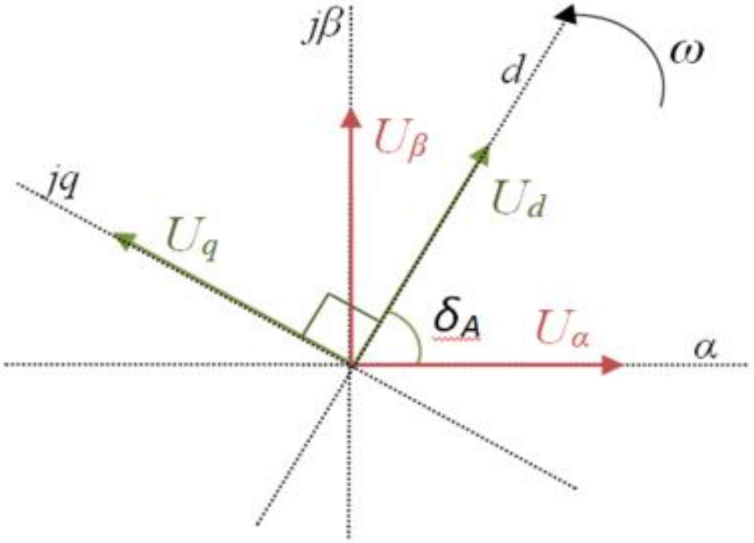


Fig. Rotation of angles with reference frame theory

dq0 Transform of Balanced Three-Phase Voltages

The following equations take a two-phase quadrature voltage along the stationary frame and transforms it into a two-phase synchronous frame (with a reference frame aligned to the voltage):

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix}$$

Note that in the *dq0* frame, the 0-component is the same as that in the $\alpha\beta0$ frame. Moreover, as we saw in the Clarke transform, the 0-component is zero for balanced three-phase systems. Therefore in the following discussion on balanced systems, the 0-component will be omitted. Consider a balanced three-phase voltage with $\alpha\beta0$ components as follows:

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = \begin{bmatrix} U_m \cos(\omega t) \\ U_m \sin(\omega t) \\ 0 \end{bmatrix}$$

The *dq0* transform of this voltage is:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}$$

Suppose that we are using a voltage reference frame and will align the synchronous frame with the voltage. Therefore $\theta = \omega t$ and:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} U_m \sin\omega t \sin(\omega t) + U_m \cos\omega t \cos(\omega t) \\ U_m \cos\omega t \sin(\omega t) - U_m \sin\omega t \cos(\omega t) \end{bmatrix}$$

$$= \begin{bmatrix} U_m \\ 0 \end{bmatrix}$$

It can be observed that since the synchronous frame is aligned to rotate with the voltage, the *d*-component corresponds to the magnitude of the voltage and the *q*-component is zero. A plot of the transformation of a voltage from a stationary *aβ0* frame into rotating *dq0* frame is shown in the figure below.

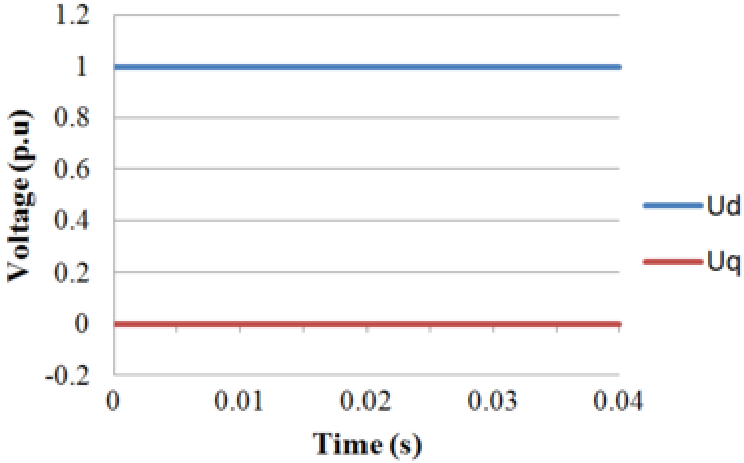


Fig. voltage of *dqo* frame

The inverse transform is as follows:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

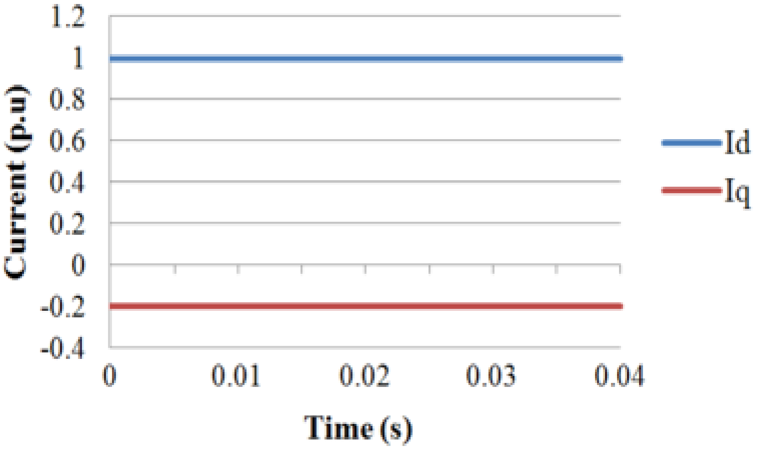


Fig. Current of *dqo* frame

Instantaneous Power in *dq0* Frame

The instantaneous active and reactive power from a set of two-phase (*dq0*) voltages and currents are:

$$p = u_d i_d + u_q i_q$$
$$q = u_q i_d - u_d i_q$$

When the synchronous frame is aligned to voltage, we saw earlier that the quadrature component: $u_q = 0$. Therefore, the power equations reduce to:

$$p = u_d i_d$$
$$q = -u_d i_q$$

The above equations show that independent control of active and reactive power is possible by means of controlling the *dq0* current components (i_d and i_q).

Controller for DSTATCOM

The three-phase reference source currents are computed using three-phase AC voltages (V_{ta}, V_{tb} and V_{tc}) and DC bus voltage (V_{dc}) of DSTATCOM. These reference supply currents consist of two components, one in-phase (I_{spdr}) and another in quadrature (I_{spqr}) with the supply voltages. The basic equations of control algorithm of DSTATCOM are as follows.

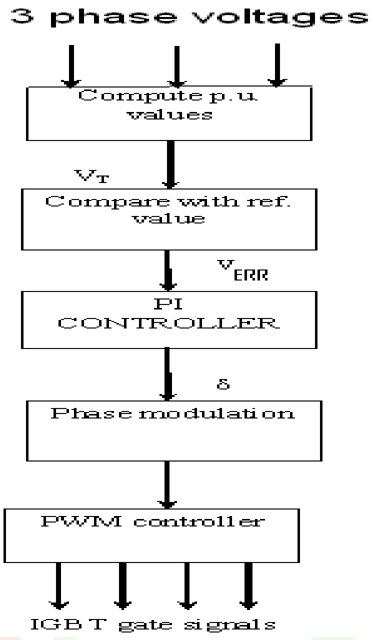


Fig 5.1 Control algorithm of DSTATCOM with PI controller.

The modulating angle is applied to the PWM generators in phase A. The angles for phases B and C are shifted by 240° and 120°, respectively. In the PWM generators, the sinusoidal

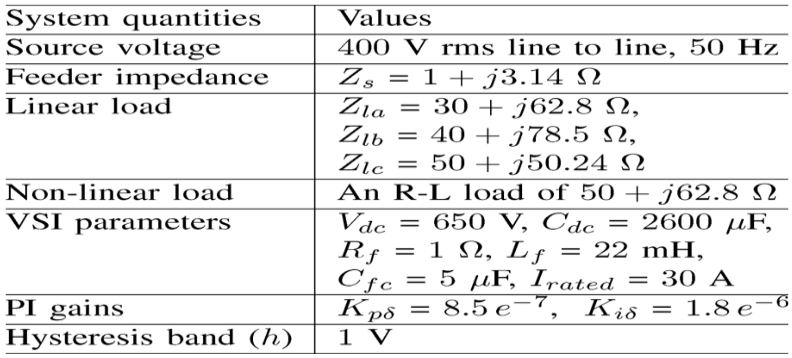
signal, V control, is phase modulated by means of the angle or delta.

Parameters of the Test System

An induction furnace load is connected in the system. The secondary winding feeds a 12-pulse thyristor-controlled rectifier and the tertiary winding another identical rectifier. Both rectifiers are connected in series including filtering coils as shown in the SIMULINK model of induction furnace in Figure10. Two parallel feeders are drawn from the source. In one feeder, induction furnace is fed without any compensating device, while in the second one, induction furnace is fed through the same source but with DSTATCOM in the circuit

Table I

System Parameters



System quantities	Values
Source voltage	400 V rms line to line, 50 Hz
Feeder impedance	$Z_s = 1 + j3.14\ \Omega$
Linear load	$Z_{la} = 30 + j62.8\ \Omega$, $Z_{lb} = 40 + j78.5\ \Omega$, $Z_{lc} = 50 + j50.24\ \Omega$
Non-linear load	An R-L load of $50 + j62.8\ \Omega$
VSI parameters	$V_{dc} = 650$ V, $C_{dc} = 2600\ \mu$F, $R_f = 1\ \Omega$, $L_f = 22$ mH, $C_{fc} = 5\ \mu$F, $I_{rated} = 30$ A
PI gains	$K_{p\delta} = 8.5\,e^{-7}$, $K_{i\delta} = 1.8\,e^{-6}$
Hysteresis band (h)	1 V

CHAPTER-3

FLEXIBLE AC TRANSMISSION SYSTEMS

3.1 Introduction

Flexible ac transmission systems, called facts, got in the recent years a well known term for higher controllability in power systems by means of power electronic devices. Several facts-devices have been introduced for various applications worldwide. A number of new types of devices are in the stage of being introduced in practice.

In most of the applications the controllability is used to avoid cost intensive or landscape requiring extensions of power systems, for instance like upgrades or additions of substations and power lines. Facts-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations.

The basic applications of facts-devices are:

- Power flow control,
- Increase of transmission capability,
- Voltage control,
- Reactive power compensation,
- Stability improvement,
- Power quality improvement,
- Power conditioning,
- Flicker mitigation,
- Interconnection of renewable and distributed generation and storages.

Figure (3.1) shows the basic idea of facts for operation limits of transmission lines for different voltage. The usage of lines for active power transmission should be ideally up to the thermal limits. Voltage and stability limits shall be shifted with the means of the several different facts devices. It can be seen that with growing line length, the opportunity for facts devices gets more and more important.

The influence of facts-devices is achieved through switched or controlled shunt compensation, series compensation or phase shift control. The devices work electrically as fast current, voltage or impedance controllers. The power electronic allows very short reaction times down to far below one second.

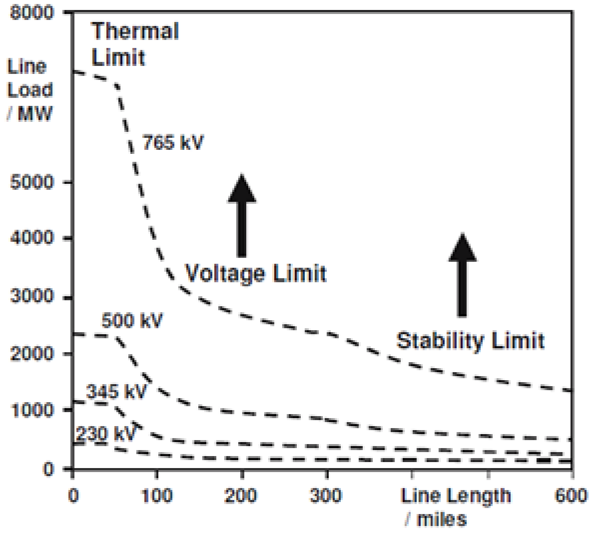


Figure 3.1 Operational limits of transimission lines for different voltage

The development of facts-devices has started with the growing capabilities of power electronic components. Devices for high power levels have been made available in converters for high and even highest voltage levels. The overall starting points are network elements influencing the reactive power or the impedance of a part of the power system. Figure (3.2) shows over view of major FACTS device a number of basic devices separated into the conventional ones and the facts-devices.

For the facts side the taxonomy in terms of 'dynamic' and 'static' needs some explanation. The term 'dynamic' is used to express the fast controllability of facts-devices provided by the power electronics. This is one of the main differentiation factors from the conventional devices. The term 'static' means that the devices have no moving parts like mechanical switches to perform the dynamic controllability. Therefore most of the facts-devices can equally be static and dynamic. The left column in figure 3.2 contains the conventional devices build out of fixed or mechanically switch able components like resistance, inductance or capacitance together with transformers. The facts-devices contain these elements as well but use additional power electronic valves or converters to switch the elements in smaller steps or with switching patterns within a cycle of the alternating current. The left column of facts-devices uses thyristor valves or converters.

These valves or converters are well known since several years. They have low losses because of their low switching frequency of once a cycle in the converters or the usage of the thyristors to simply bridge impedances in the valves.

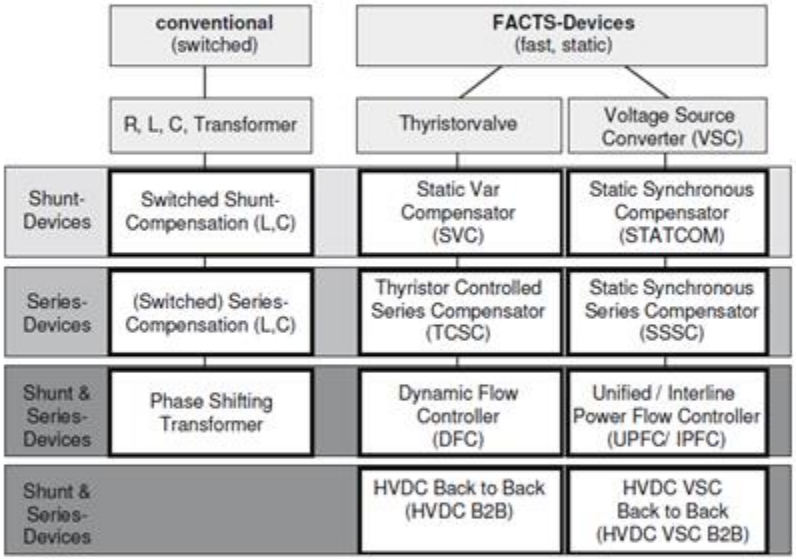


Figure 3.2 over view of major FACTS device

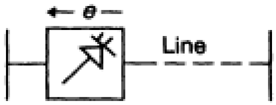
The right column of facts-devices contains more advanced technology of voltage source converters based today mainly on insulated gate bipolar transistors (IGBT) or insulated gate commutated thyristors (IGCT). Voltage source converters provide a free controllable voltage in magnitude and phase due to a pulse width modulation of the igbts or IGCTS. High modulation frequencies allow to get low harmonics in the output signal and even to compensate disturbances coming from the network. The disadvantage is that with an increasing switching frequency, the losses are increasing as well. Therefore special designs of the converters are required to compensate this.

BASIC TYPES OF FACTS CONTROLLERS

In general, FACTS Controllers can be divided into four categories:

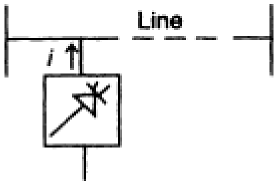
- *Series Controllers*
- *Shunt Controllers*
- *Combined series-series Controllers*
- *Combined series-shunt Controllers*

Series Controllers: [Figure 1.4(b)] The series Controller could be a variable impedance, such as capacitor, reactor, etc., or a power electronics based variable source of main frequency, subsynchronous and harmonic frequencies (or a combination) to serve the desired need. In principle, all series Controllers inject voltage in series with the line. Even variable impedance multiplied by the current flow through it, represents an injected series voltage in the line. As long as the voltage is in phase quadrature with the line current, the series Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.



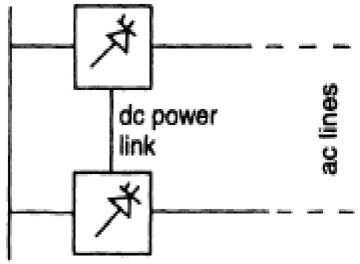
Fig

Shunt Controllers: [Figure 1.4(c)] As in the case of series Controllers, the shunt Controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt Controllers inject current into the system at the point of connection. Even variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.



Fig

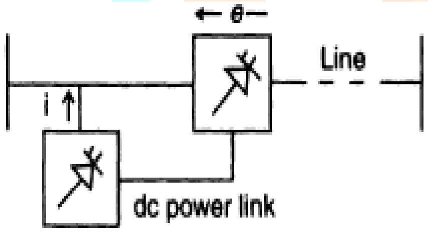
Combined series-series Controllers: [Figure 1.4(d)] This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. Or it could be a unified Controller, Figure 1.4(d), in which series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. The real power transfer capability of the unified series-series Controller, referred to as *Interline Power Flow Controller,* makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system. Note that the term "unified" here means that the de terminals of all Controller converters are all connected together for real power transfer.



Fig

Combined series-shunt Controllers: [Figures 1.4(e) and 1.4(f)] This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated

manner [Figure 1.4(e)], or a *Unified Power Flow Controller* with series and shunt elements [Figure 1.4(f)]. In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller. However, when the shunt and series Controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link.



Fig

3.2 CONFIGURATIONS OF FACTS-DEVICES:

3.2.1 Shunt devices

The most used facts-device is the svc or the version with voltage source converter called STATCOM. These shunt devices are operating as reactive power compensators.

The main applications in transmission, distribution and industrial networks are:

- Reduction of unwanted reactive power flows and therefore reduced network losses.
- Keeping of contractual power exchanges with balanced reactive power.
- Compensation of consumers and improvement of power quality especially with huge demand fluctuations like industrial machines, metal melting plants, railway or underground train systems.
- Compensation of thyristor converters e.g. in conventional HVDC lines.
- Improvement of static or transient stability.

3.2.2 SVC

Electrical loads both generate and absorb reactive power. Since the transmitted load varies considerably from one hour to another, the reactive power balance in a grid varies as well. The result can be unacceptable voltage amplitude variations or even a voltage depression, at the extreme a voltage collapse.

A rapidly operating static Var compensator (SVC) can continuously provide the reactive power required to control dynamic voltage oscillations under various system conditions and thereby improve the power system transmission and distribution stability.

Applications of the SVC systems in transmission systems:

A. To increase active power transfer capacity and transient stability margin

B. To damp power oscillations

C. To achieve effective voltage control

In addition, SVC's are also used

1. In transmission systems

A. To reduce temporary over voltages

B. To damp sub synchronous resonances

C. To damp power oscillations in interconnected power systems

2. In traction systems

A. To balance loads

B. To improve power factor

C. To improve voltage regulation

3.3 STATCOM

The STATCOM is a solid-state-based power converter version of the SVC. Operating as a shunt-connected SVC, its capacitive or inductive output currents can be controlled independently from its terminal AC bus voltage. Because of the fast-switching characteristic of power converters, STATCOM provides much faster response as compared to the SVC. In addition, in the event of a rapid change in system voltage, the capacitor voltage does not change instantaneously; therefore, STATCOM effectively reacts for the desired responses. For example, if the system voltage drops for any reason, there is a tendency for STATCOM to inject capacitive power to support the dipped voltages.

STATCOM is capable of high dynamic performance and its compensation does not depend on the common coupling voltage. Therefore, STATCOM is very effective during the power system disturbances.

Moreover, much research confirms several advantages of STATCOM. *These advantages compared to other shunt compensators include:*

- Size, weight, and cost reduction
- Equality of lagging and leading output
- Precise and continuous reactive power control with fast response
- Possible active harmonic filter capability

This chapter describes the structure, basic operating principle and characteristics of STATCOM. In addition, the concept of voltage source converters and the corresponding control techniques are illustrated.

3.3.1 Structure of STATCOM

Basically, STATCOM is comprised of three main parts (as seen from Figure below 3.3) a voltage source converter (VSC), a step-up coupling transformer, and a controller. In a very-high-voltage system, the leakage inductances of the step-up power transformers can function as coupling reactors. The main purpose of the coupling inductors is to filter out the current harmonic components that are generated mainly by the pulsating output voltage of the power converters.

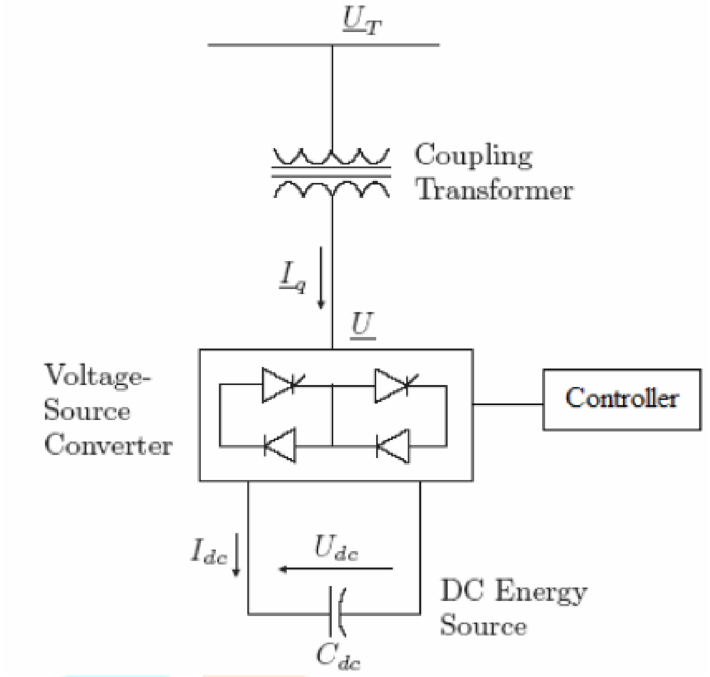


Figure 3.3 Reactive power generation by a STATCOM

3.3.2 Control of STATCOM

The controller of a STATCOM operates the converter in a particular way that the phase angle between the converter voltage and the transmission line voltage is dynamically adjusted and synchronized so that the STATCOM generates or absorbs desired VAR at the point of coupling connection.

Figure (3.4) shows a simplified diagram of the STATCOM operating in inductive or capacitive load with a converter voltage source __1*E* and a tie reactance, connected to a system with a voltage source, and a The venin reactance, $XTIEX\_THV_{TH}$.

3.3.3 Two Modes of Operation

There are two modes of operation for a STATCOM, inductive mode and the capacitive mode. The STATCOM regards an inductive reactance connected at its terminal when the converter voltage is higher than the transmission line voltage. Hence, from the system's point of view, it regards the STATCOM as a capacitive reactance and the STATCOM is considered to be operating in a capacitive mode. Similarly, when the system voltage is higher than the converter voltage, the system regards an inductive reactance connected at its terminal. Hence, the STATCOM regards the system as a capacitive reactance and the STATCOM is considered to be operating in an inductive mode

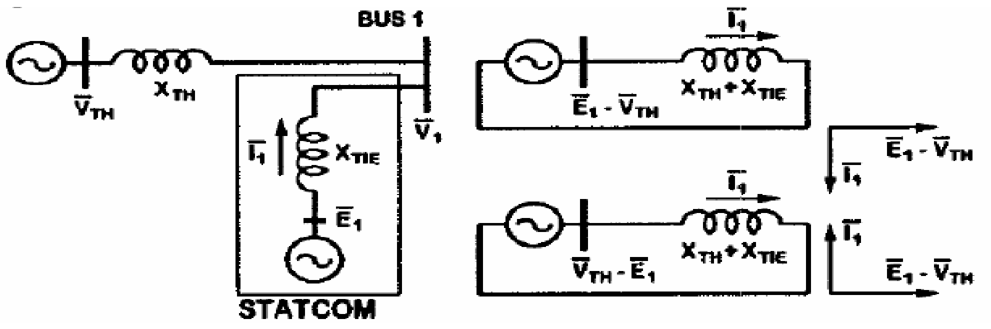


Figure 3.4 STATCOM operating in inductive or capacitive modes

In other words, looking at the pharos diagrams on the right of Figure, when1I, the reactive current component of the STATCOM, leads ($THVE-1$) by 90°, it is in inductive mode and when it lags by 90°, it is in capacitive mode..

3.3.4 Current Controlled STATCOM

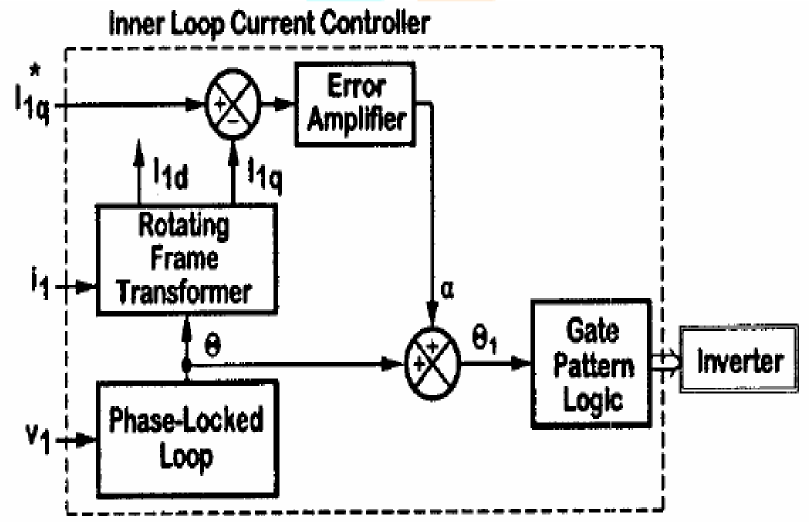


Figure 3.5 Current controlled block diagram of STATCOM

Figure (3.5) above shows the reactive current control block diagram of the STATCOM. An instantaneous three-phase set of line voltages, v_l, at BUS 1 is used to calculate the reference angle, θ, which is phase-locked to the phase a of the line voltage, v_{la} . An instantaneous three-phase set of measured converter currents, i_l, is decomposed into its real or direct component, I_{1d}, and reactive or quadrature component, I_{1q}, respectively. The quadrature component is compared with the desired reference value, I_{1q}^* and the error is passed through an error amplifier which produces a relative angle, α, of the converter voltage with respect to the transmission line voltage. The phase angle, θ_1, of the converter voltage is calculated by adding the relative angle, α, of the converter voltage and the phase – lock-loop angle, θ. The reference quadrature component, I_{1q}^*, of the converter current is defined to be either *positive* if the STATCOM is emulating an inductive reactance or *negative* if it is emulating a capacitive reactance. The DC capacitor voltage, v_{DC}, is dynamically adjusted in relation with the converter voltage. The control scheme described above shows the implementation of the inner current control loop which regulates the reactive current flow through the STATCOM regardless of the line voltage.

3.3.5 Voltage Controlled STATCOM

In regulating the line voltage, an outer voltage control loop must be implemented. The outer voltage control loop would automatically determine the reference reactive current for the inner current control loop which, in turn, will regulate the line voltage.

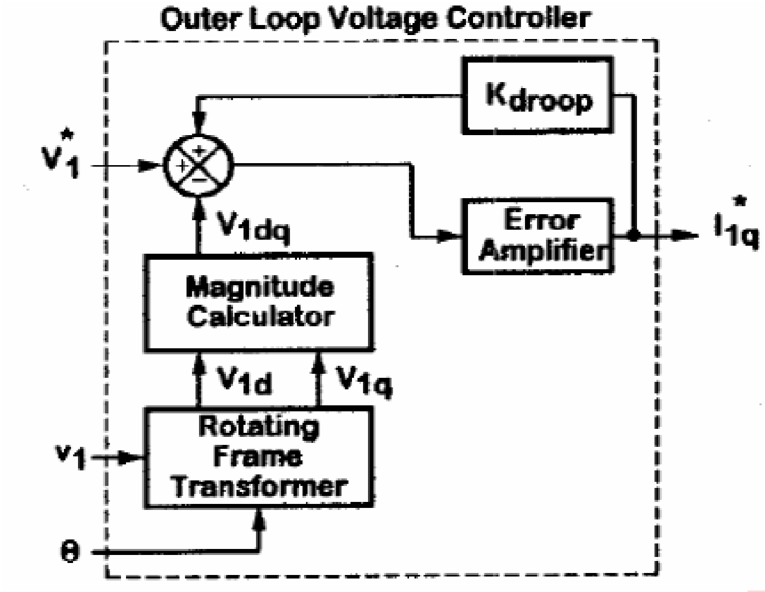


Figure 3.6 Voltage controlled block diagram of STATCOM

Figure (3.6) shows a voltage control block diagram of the STATCOM. An instantaneous three-phase set of measured line voltages, v_1, at BUS 1 is decomposed into its real or direct component, V_{1d}, and reactive or quadrature component, V_{1q}, is compared with the desired reference value, V_1^*, (adjusted by the droop factor, K_{droop}) and the error is passed through an error amplifier which produces the reference current, I_{1q}^*, for the inner current control loop. The droop factor, K_{droop}, is defined as the allowable voltage error at the rated reactive current flow through the STATCOM.

3.3.6 Basic operating principles of STATCOM

The STATCOM is connected to the power system at a PCC (point of common coupling), through a step-up coupling transformer, where the voltage-quality problem is a concern. The PCC is also known as the terminal for which the terminal voltage is U_T.

All required voltages and currents are measured and are fed into the controller to be compared with the commands. The controller then performs feedback control and outputs a set of switching signals (firing angle) to drive the main semiconductor switches of the power converter accordingly to either increase the voltage or to decrease it accordingly. A

STATCOM is a controlled reactive-power source. It provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors or capacitor banks. Using the controller, the VSC and the coupling transformer, the STATCOM operation is illustrated in Figure (3.7) below.

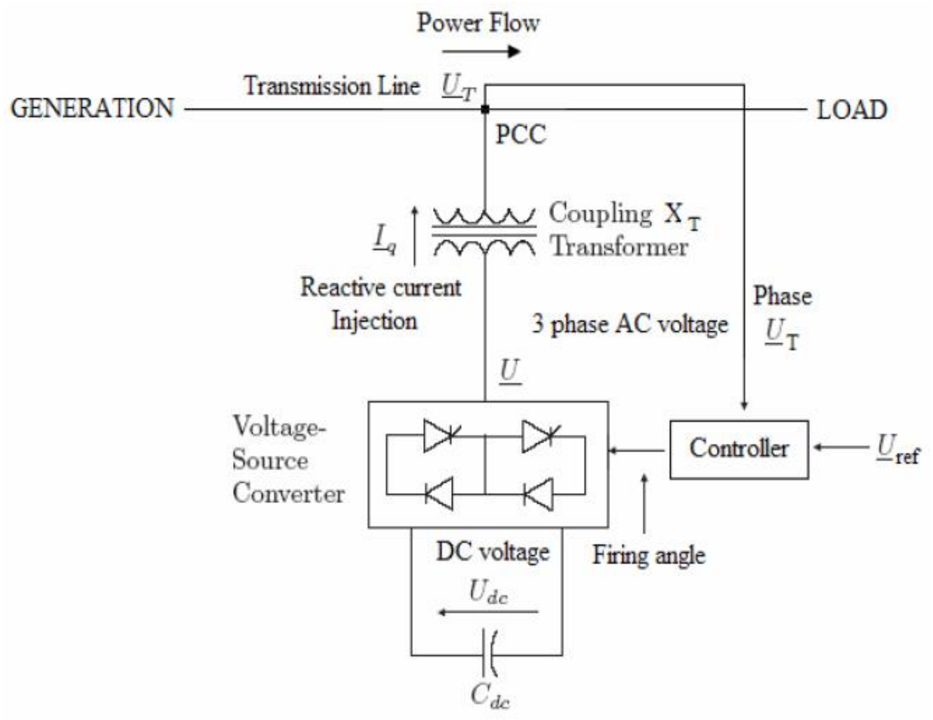


Figure 3.7 STATCOM operations in a power system

The charged capacitor C_{dc} provides a DC voltage, U_{dc} to the converter, which produces a set of controllable three-phase output voltages, U in synchronism with the AC system. The synchronism of the three-phase output voltage with the transmission line voltage has to be performed by an external controller. The amount of desired voltage across STATCOM, which is the voltage reference, Uref, is set manually to the controller. The voltage control is thereby to match U_T with Uref which has been elaborated. This matching of voltages is done by varying the amplitude of the output voltage U, which is done by the firing angle set by the controller. The controller thus sets U_T equivalent to the Uref.

The reactive power exchange between the converter and the AC system can also be controlled in eq (1). This reactive power exchange is the reactive current injected by the STATCOM, which is the current from the capacitor produced by absorbing real power from the AC system.

$$I_q=\frac{\underline{U}_T-\underline{U}_{eq}}{X_{eq}} \tag{1}$$

Where I_q is the reactive current injected by the STATCOM

U_T is the STATCOM terminal voltage

U_{eq} is the equivalent the venin voltage seen by the STATCOM

X_{eq} is the equivalent the venin reactance of the power system seen by the STATCOM

If the amplitude of the output voltage U is increased above that of the AC system voltage, U_T, a leading current is produced, i.e. the STATCOM is seen as a conductor by the AC system and reactive power is generated. Decreasing the amplitude of the output voltage below that of the AC system, a lagging current results and the STATCOM is seen as an inductor. In this case reactive power is absorbed. If the amplitudes are equal no power exchange takes place.

3.3.7 Characteristics of Statcom

The derivation of the formula for the transmitted active power employs considerable calculations. Using the variables defined in Figure (3.8) below and applying Kirchhoff's laws the following equations can be written;

$$\underline{I}_2=\frac{U_T-U_2}{JX_2}=\frac{(U_1-jI_1X_1)-U_2}{JX_2} \tag{2}$$

$$\underline{\mathrm{I}}_2=\underline{\mathrm{I}}_1-\underline{\mathrm{I}}_\mathrm{q} \tag{3}$$

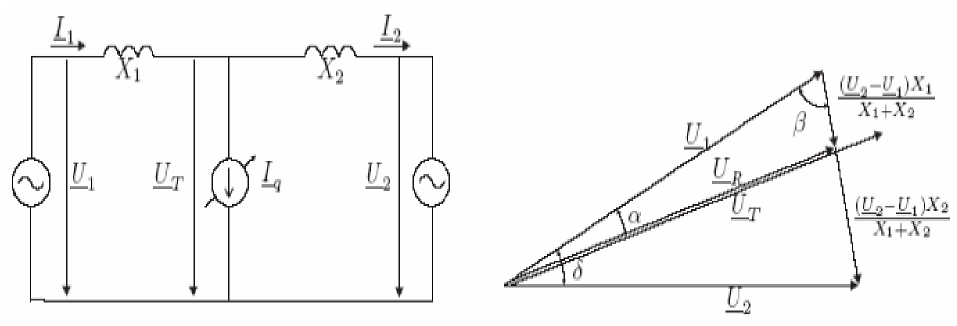


Figure 3.8 Two machine system with STATCOM

By equaling right-hand terms of the above formulas eq 2,3, a formula as shown in eq (4,5) for the current I_1, U_T is obtained as

$$\underline{I}_1=\frac{U_1-U_2}{j(X_1+X_2)}+I_q\frac{X_2}{(X_1+X_2)} \tag{4}$$

$$\underline{U}_T=\underline{U}_1-j\underline{I}_1\underline{X}_1=\underline{U}_1-\frac{(\underline{U}_1-\underline{U}_2)X_1}{(X_1+X_2)}=j_{\underline{I}_q}.\frac{X_1X_2}{(X_1+X_2)}=\underline{U}_R-J\underline{I}_q.\frac{X_1X_2}{(X_1+X_2)} \tag{5}$$

Where U_R is the STATCOM terminal voltage if the STATCOM is out of operation, i.e. when $I_q = 0$. The fact that I_q is shifted by 90◦ with regard to U_R can be used to express I_q as Eq (6) is given bellow

$$\underline{I}_q=jI_q.\frac{U_R}{U_R} \tag{6}$$

$$\underline{U}_T = \underline{U}_R + U_q \frac{\underline{U}_R}{U_R} . \frac{X_1X_2}{(X_1+X_2)} = \underline{U}_R(1 + \frac{I_q}{U_R} . \frac{X_1X_2}{(X_1+X_2)}) \quad (7)$$

Applying the sine law to the diagram in Figure (4.8) below the following two equations result

$$\frac{\sin\beta}{U_2} = \frac{\sin\delta}{|\underline{U}_1 - \underline{U}_2|} \quad (8)$$

$$\frac{\sin\propto}{|\underline{U}_1 - \underline{U}_2| \frac{X_1}{(X_1+X_2)}} = \frac{\sin\beta}{U_R} \quad (9)$$

from which the formula is eq (10) for sin α is derived.

$$\sin\alpha = \frac{U_2 \sin\delta X_1}{U_R(X_1+X_2)} \quad (10)$$

The formula is eq(11) for the transmitted active power can be given as

$$P=P_1=P_2=\frac{U_T U_1}{X_1} \sin\alpha = \frac{U_1 U_2 \sin\delta}{(X_1+X_2)} . \frac{U_T}{U_R} \quad (11)$$

To dispose of the term U_R the cosine law is applied to the diagram in Figure above Therefore,

$$U_R = |\underline{U}_R| = \left|\frac{\underline{U}_1 X_2 + U_2 X_1}{(X_1+X_2)}\right| = \frac{\sqrt{U_1^2 X_2^2 + U_2^2 x_1^2 + 2U_1 U_2 X_1 X_2 \cos\delta}}{(X_1+X_2)} \quad (12)$$

$$P = \frac{U_1 U_2 \sin\delta}{(X_1+X_2)}(1 + \frac{I_q}{U_R} . \frac{X_1X_2}{(X_1+X_2)}) \quad (13)$$

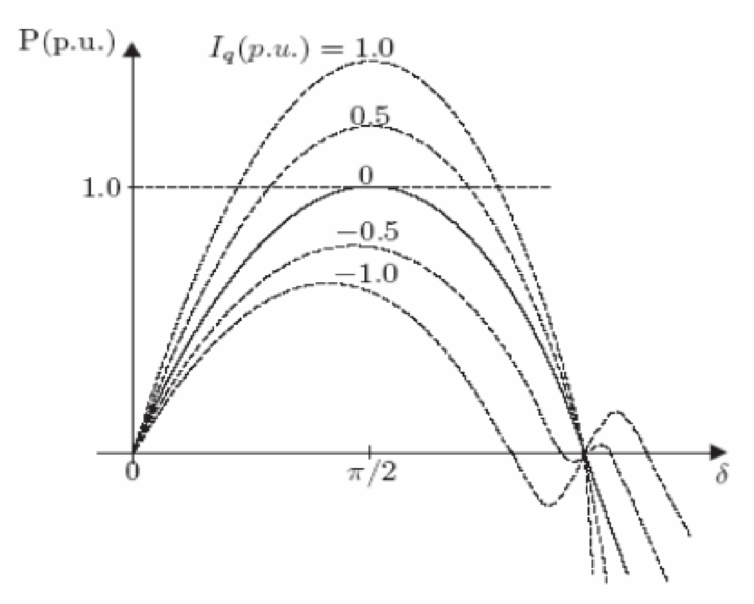


Figure 3.9 Transmitted power versus transmission angle characteristic of a STATCOM

With these concepts of STATCOM, it is thus important to utilize these principles in accommodating shunt compensation to any system. Transmitted power versus transmission angle characteristic of a STATCOM as shown in above figure (3.9), Since this thesis only reflects on the voltage control and power increase, the requirements of the STATCOM would be further elaborated.

3.4 SINGLE-PHASE VOLTAGE SOURCE INVERTERS

Single-phase voltage source inverters (VSIs) can be found as half-bridge and full-bridge topologies. Although the power range they cover is the low one, they are widely used in power supplies, single-phase UPSs, and currently to form elaborate high-power static power topologies, such as for instance, the multi cell configurations that are reviewed. The main features of both approaches are reviewed and presented in the following.

3.4.1 Half-bridge VSI

Figure (3.10) shows the power topology of a half-bridge VSI, where two large capacitors are required to provide a neutral point N, such that each capacitor maintains a constant voltage vi=2. Because the current harmonics injected by the operation of the inverter are low-order harmonics, a set of large capacitors (C. and Cÿ) is required. It is clear that both switches S. and Sÿ cannot be on simultaneously because a short circuit across the dc link voltage source vi would be produced. There are two defined (states 1 and 2) and one undefined (state 3) switch state . In order to avoid the short circuit across the dc bus and the undefined ac output voltage condition, the modulating technique should always ensure that at any instant either the top or the bottom switch of the inverter leg is on.

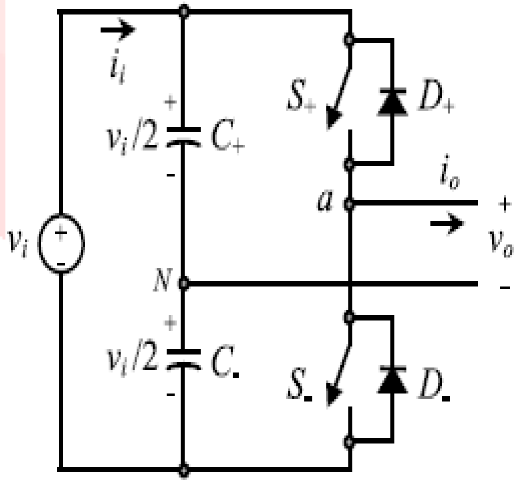


Figure 3.10 Single-phase half-bridge VSI.

Figure shows the ideal waveforms associated with the half-bridge inverter shown in Fig.(3.10). The states for the switches S. and Sÿ are defined by the modulating technique, which in this case is a carrier-based PWM.

3.4.2 The Carrier-Based Pulse width Modulation (PWM) Technique

As mentioned earlier, it is desired that the ac output voltage. Va N follow a given waveform (e.g., sinusoidal) on a continuous basis by properly switching the power valves. The carrier-based PWM technique fulfils such a requirement as it defines the on and off states of the switches of one leg of a VSI by comparing a modulating signal Vc (desired ac output voltage) and a triangular waveform V_d (carrier signal). In practice, when Vc > V_D the switch S. is on and the switch is off; similarly, when Vc < V_D the switch S. is off and the switch Sӱ is on. A special case is when the modulating signal Vc is a sinusoidal at frequency fc and amplitude ^Vc , and the triangular signal V_D is at frequency f_D and amplitude ^ V_D. This is the sinusoidal PWM (SPWM) scheme. In this case, the modulation index ma (also known as the amplitude-modulation ratio) is defined as eq (14)

$$m_a=\frac{ΰ_c}{ΰ_\Delta} \tag{14}$$

And the normalized carrier frequency mf (also known as the frequency-modulation ratio) is eq (15)

$$M_f=\frac{f_\Delta}{f_c} \tag{15}$$

Figure 5.2(e) clearly shows that the ac output voltage $v_o = v_{aN}$ is basically a sinusoidal waveform plus harmonics, which features: (a) the amplitude of the fundamental component of the ac output voltage $\hat{v}_{o1}$ satisfying the following expression eq (16)

$$Ÿ_{01}=ΰ_{aN1}=\frac{v_i}{2}m_a \tag{16}$$

The PWM technique allows an ac output voltage to be generated that tracks a given modulating signal. A special case is the SPWM technique (the modulating signal is a sinusoidal) that provides in the linear region an ac output voltage that varies linearly as a function of the modulation index and the harmonics are at well-defined frequencies and amplitudes. These features simplify the design of filtering components. Unfortunately, the maximum amplitude of the fundamental ac voltage is V_i =2 in this operating mode.

Higher voltages are obtained by using the over modulation region (Ma > 1); however, low-order harmonics appear in the ac output voltage. Very large values of the modulation index (Ma > 3:24) lead to a totally square ac output voltage that is considered as the square-wave modulating technique that is discussed in the next section.

Pulse Width Modulation techniques are used to reduce the harmonics in the system. These reduce the lower order harmonics. The disadvantages of PWM Techniques are switch life is reducing due to the very low ON and OFF times. Analysis of PWM techniques are done by using Fourier Transforms.

3.4.3 Full-bridge VSI

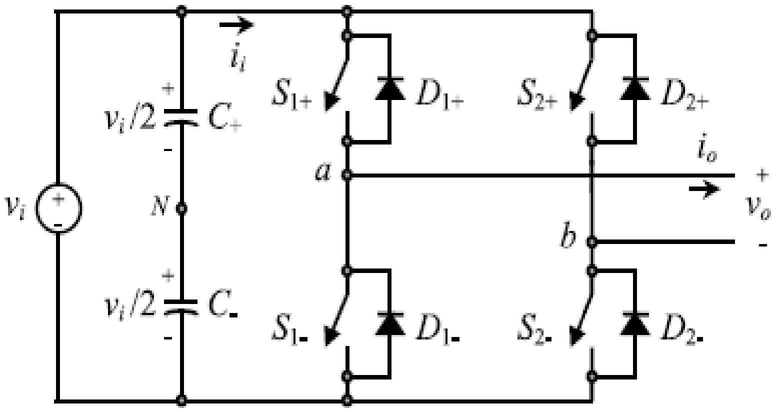


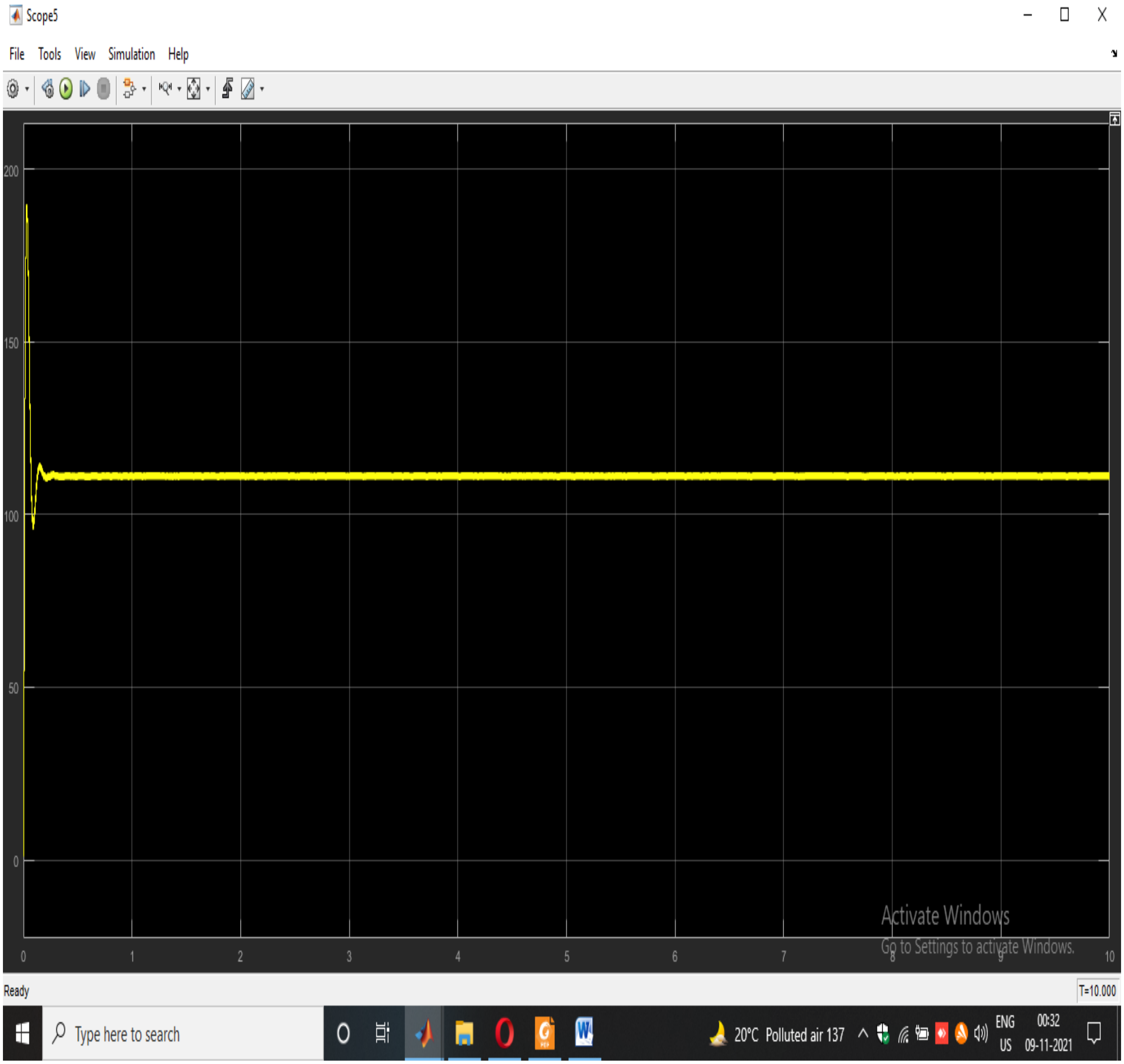
Figure 3.11 Single-phase full-bridge VSI.

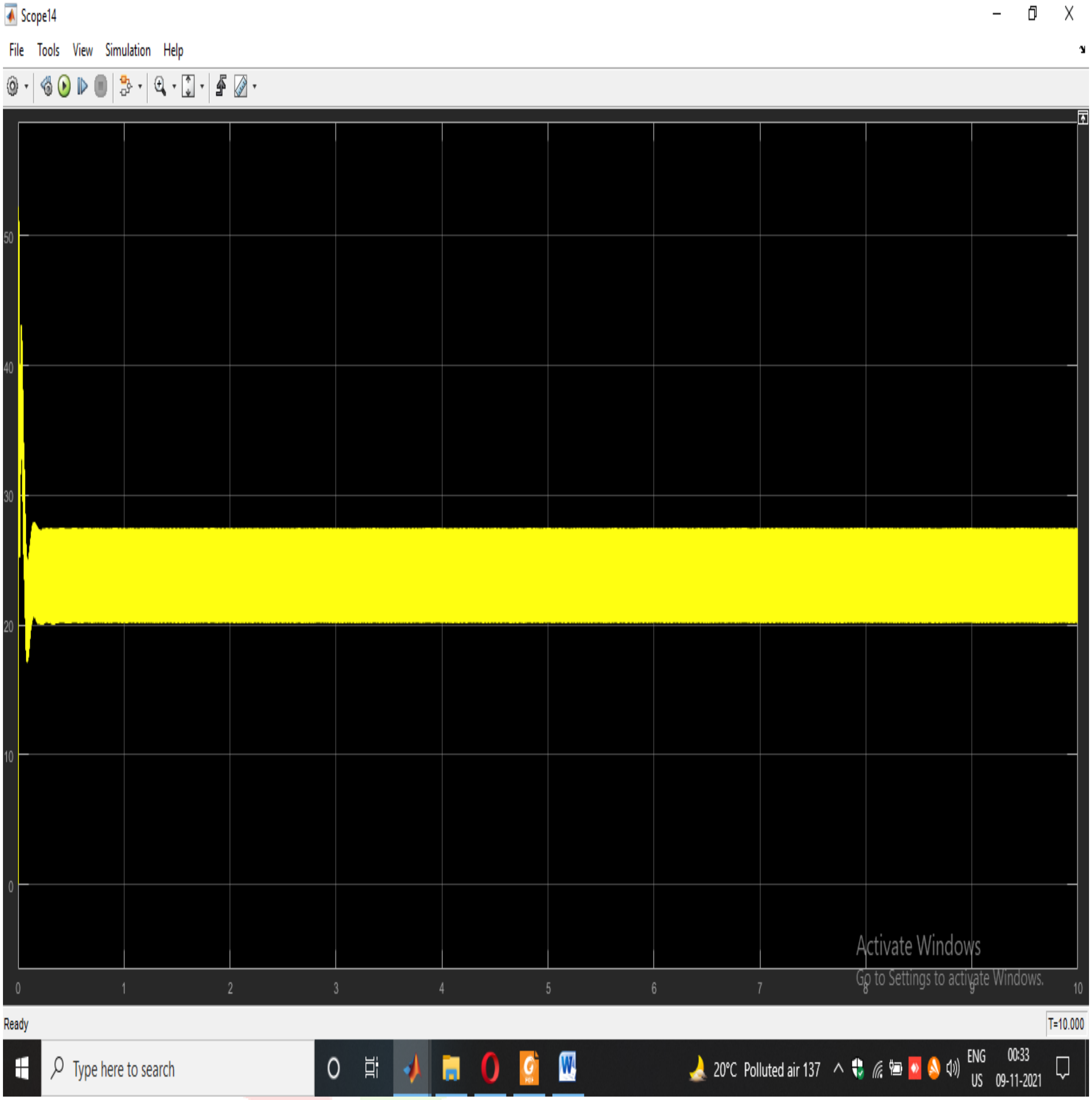
Figure (3.11) shows the power topology of a full-bridge VSI. This inverter is similar to the half-bridge inverter; however, a second leg provides the neutral point to the load. As expected, both switches s_{1+} and s_{1-} (or s_{2+} and s_{2-}) cannot be on simultaneously because a short circuit across the dc link voltage source vi would be produced. There are four defined (states 1, 2, 3, and 4) and one undefined (state 5) switch states.

The undefined condition should be avoided so as to be always capable of defining the ac output voltage. In order to avoid the short circuit across the dc bus and the undefined ac output voltage condition, the modulating technique should ensure that either the top or the bottom switch of each leg is on at any instant. It can be observed that the ac output voltage can take values up to the dc link value vi , which is twice that obtained with half-bridge VSI topologies. Several modulating techniques have been developed that are applicable to full-bridge VSIs. Among them are the PWM (bipolar and unipolar) technique.

CHAPTER-4

RESULT

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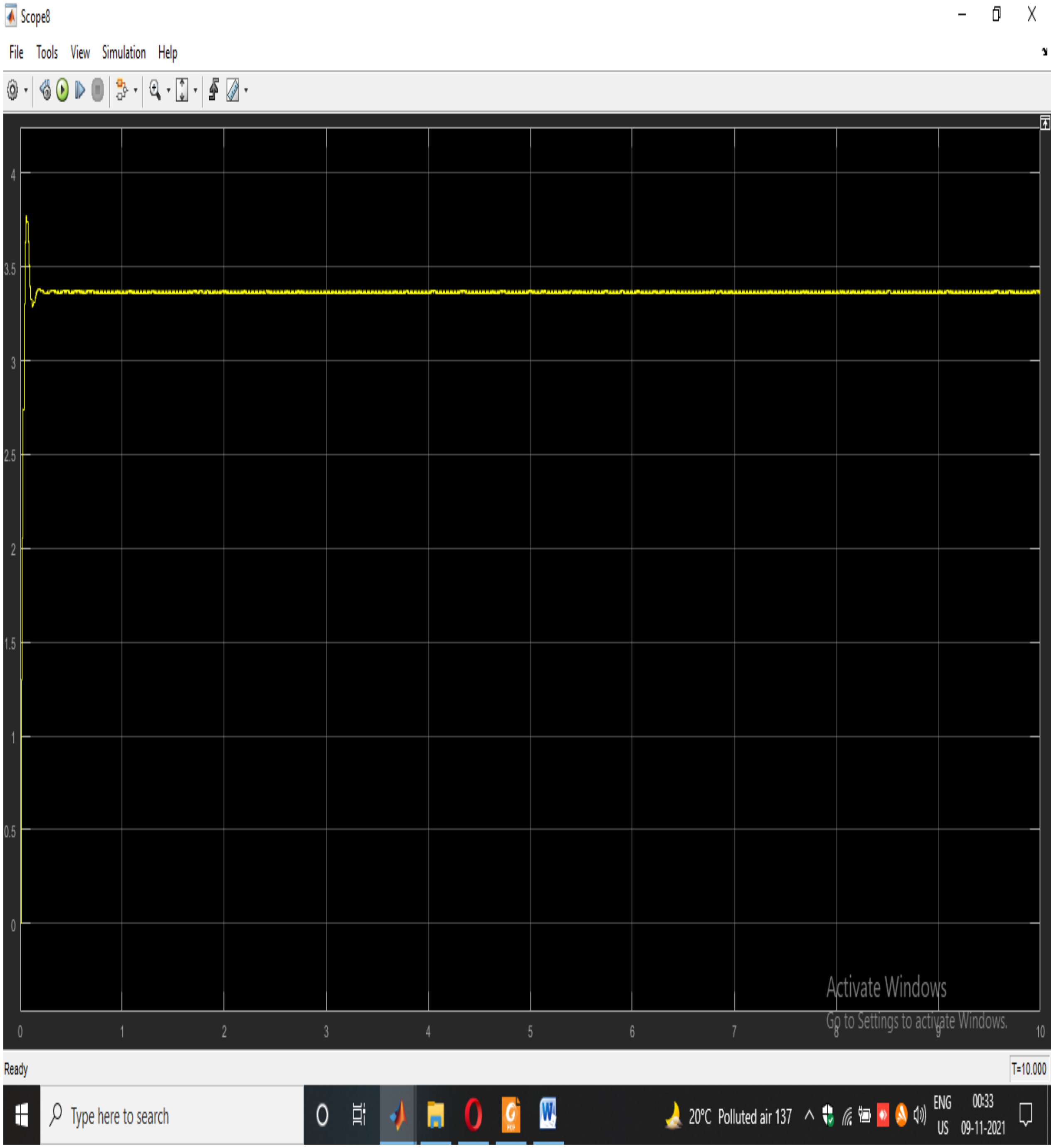
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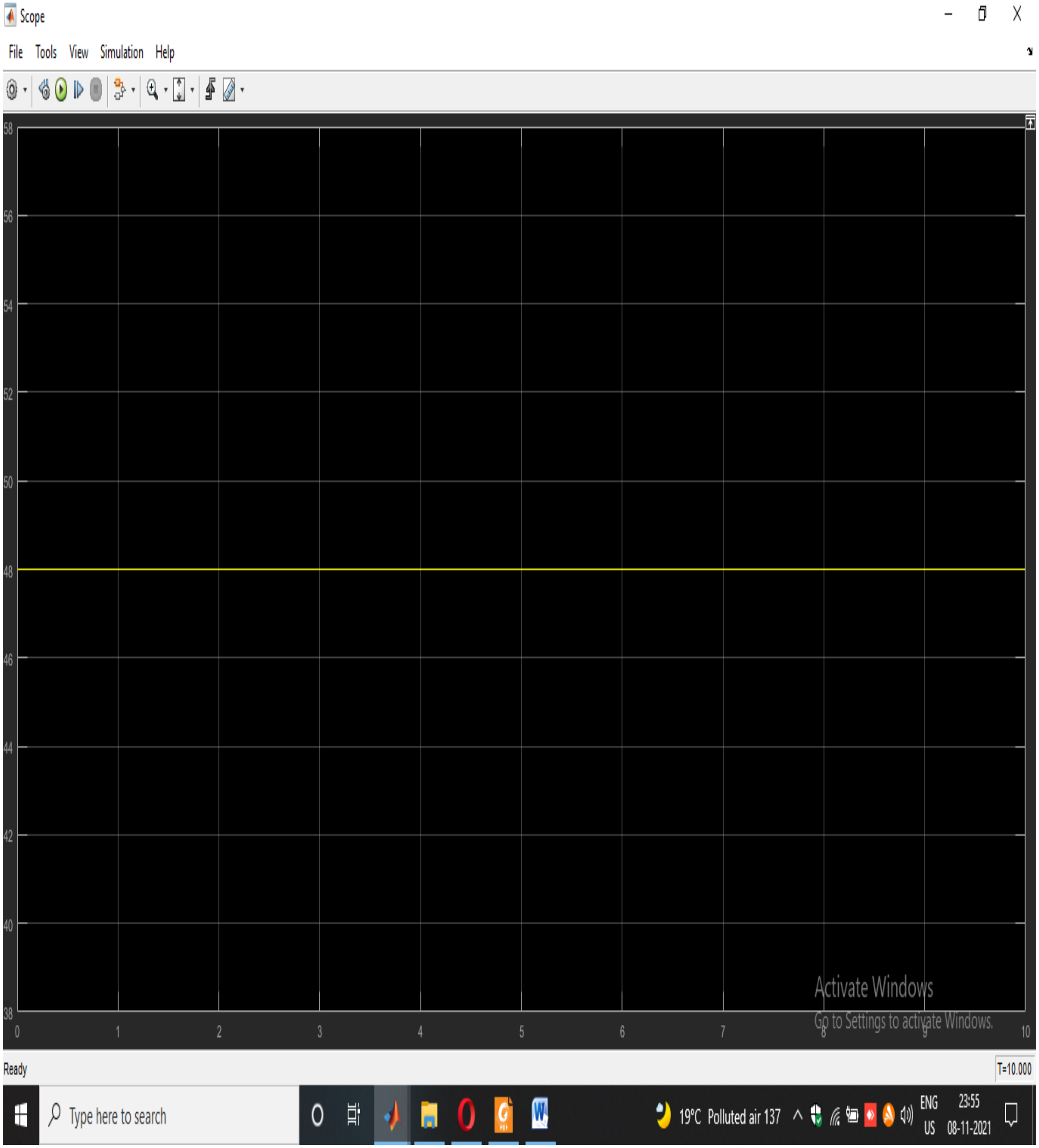
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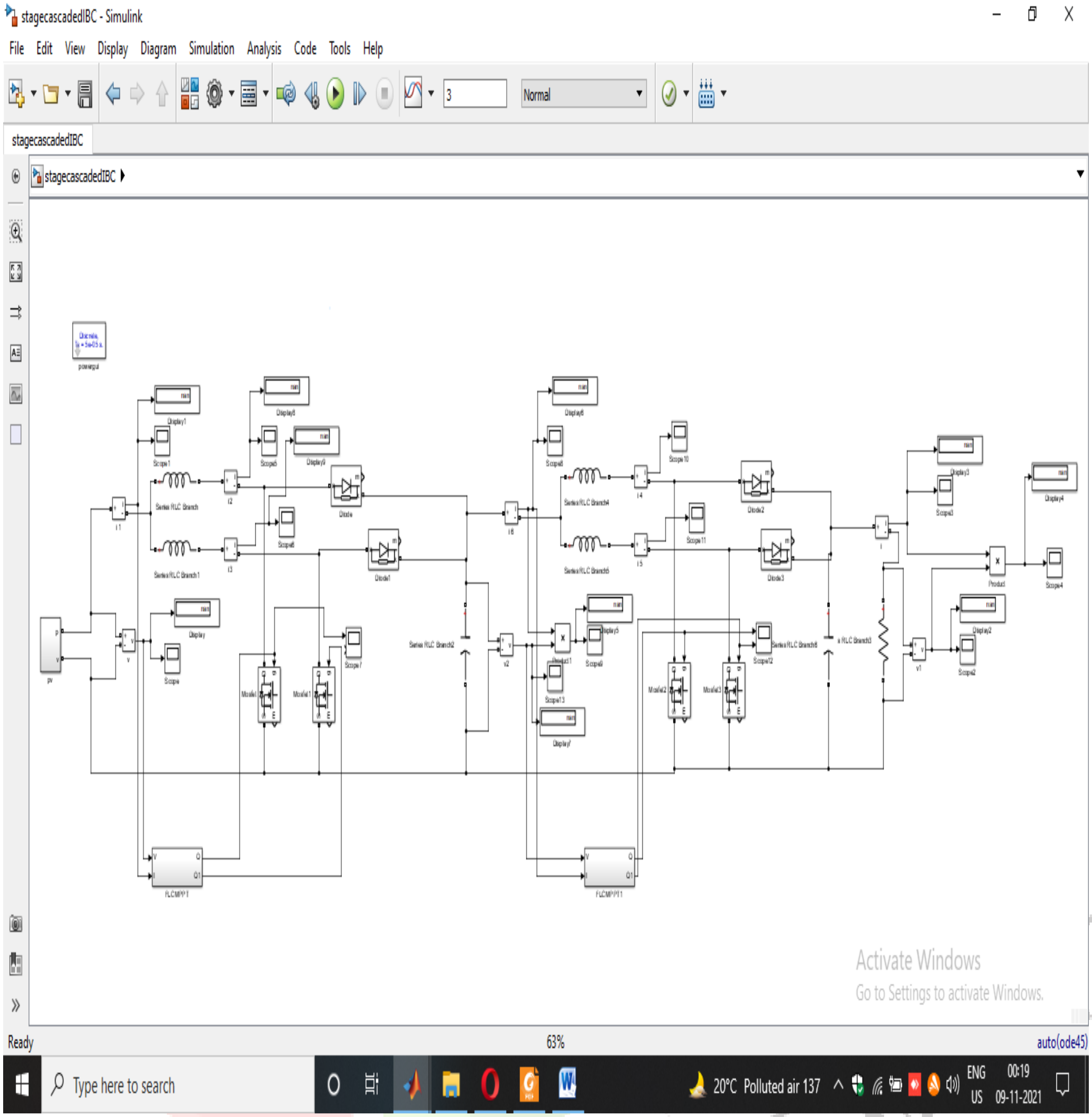
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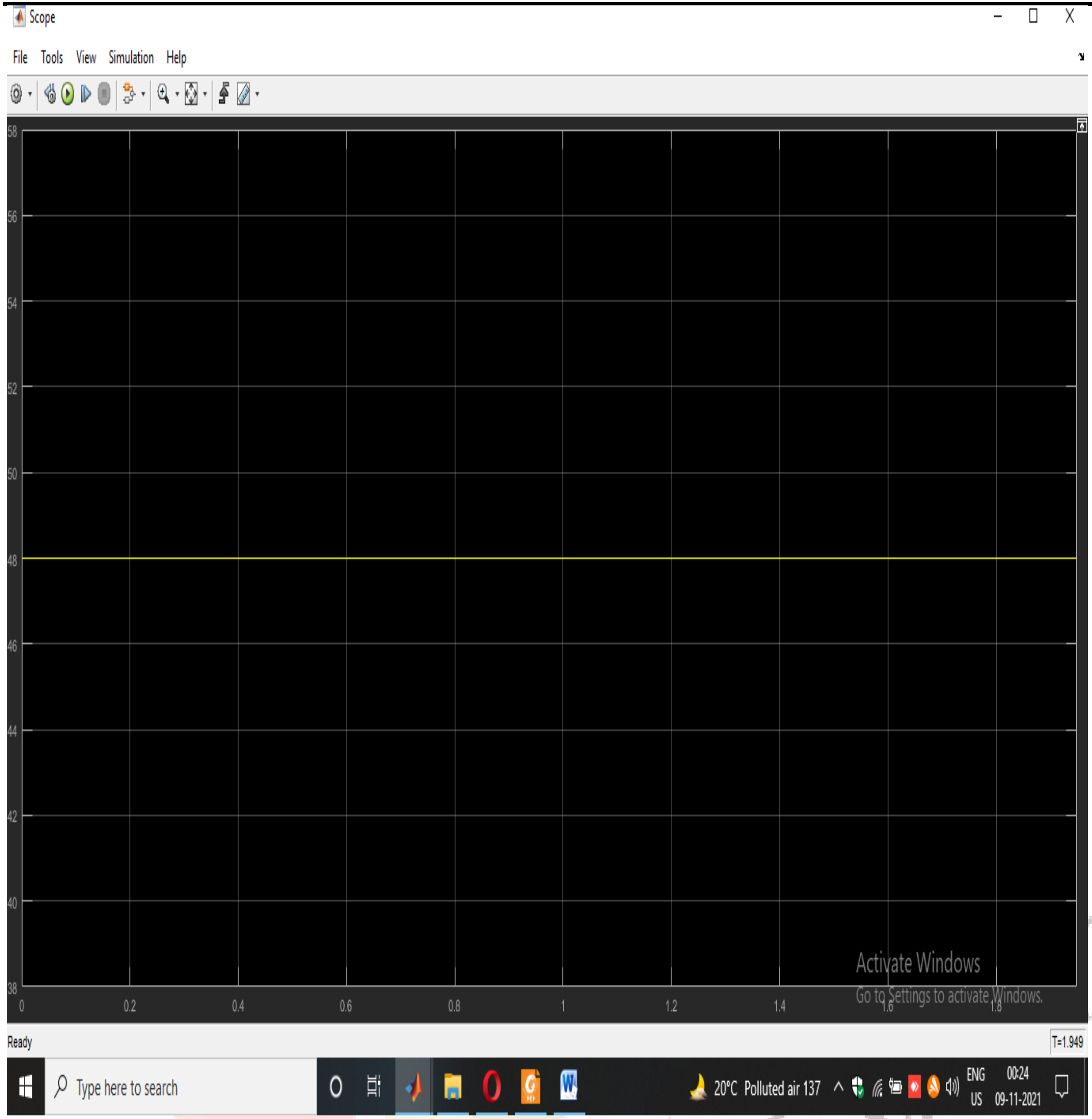
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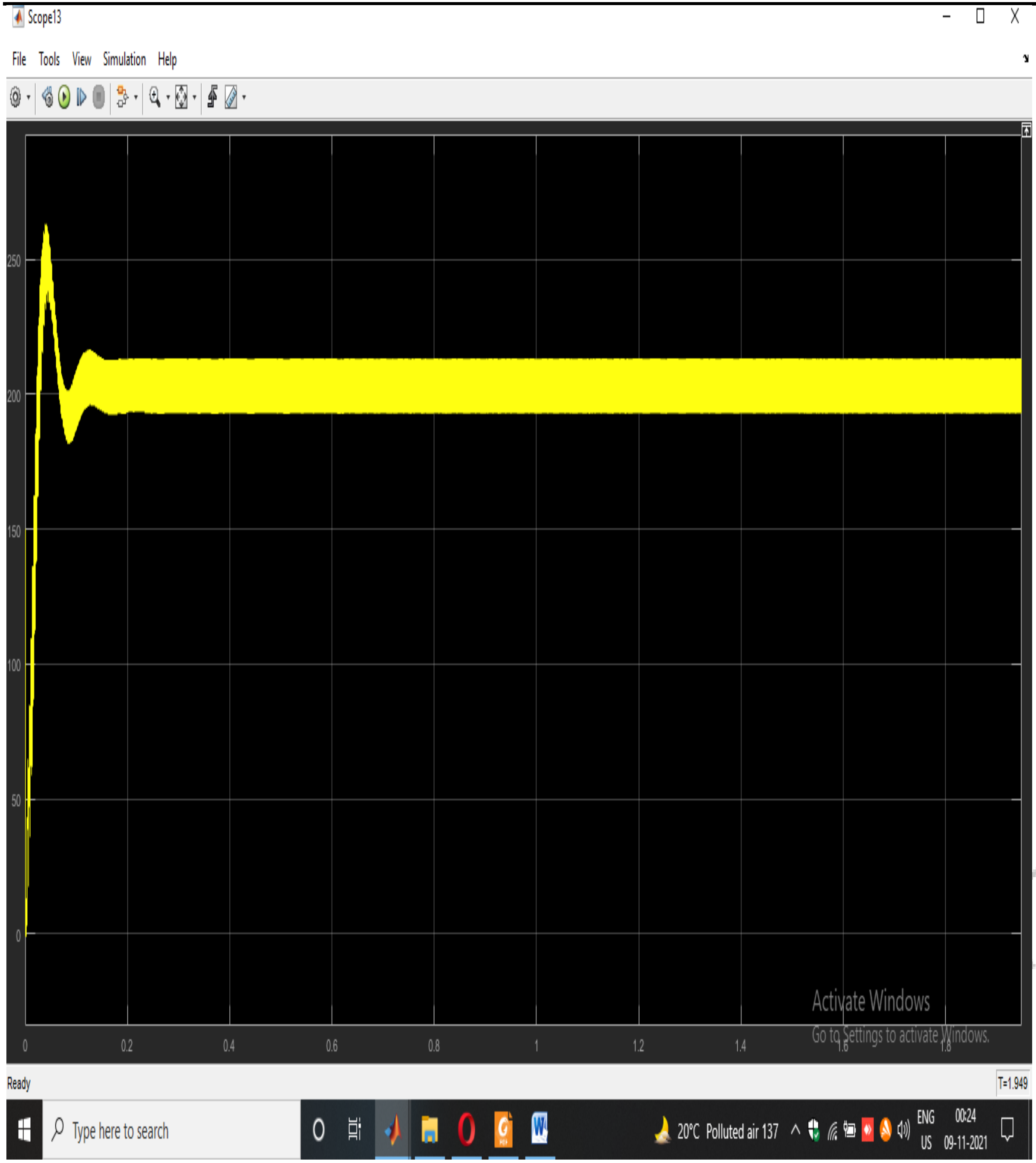
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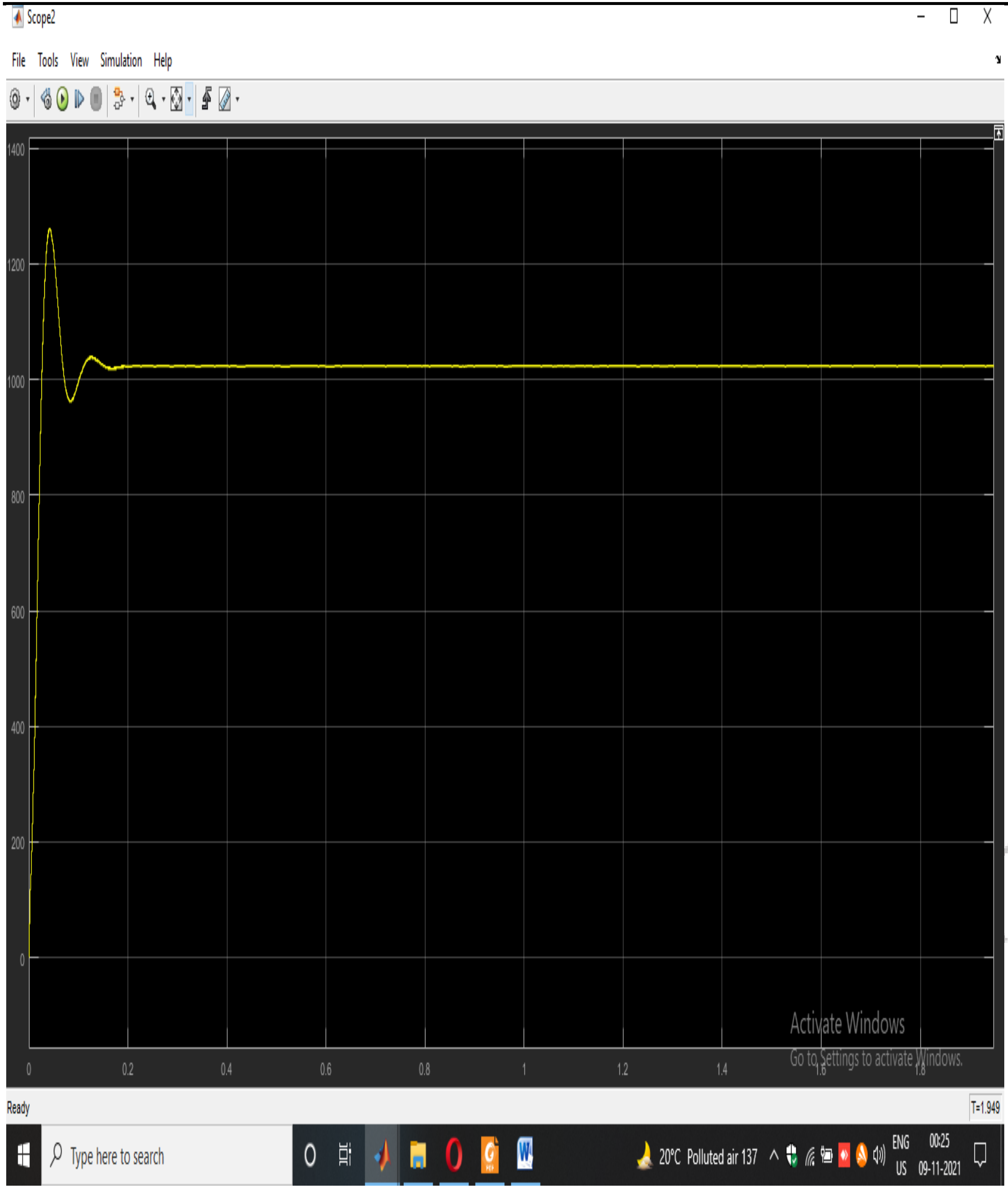
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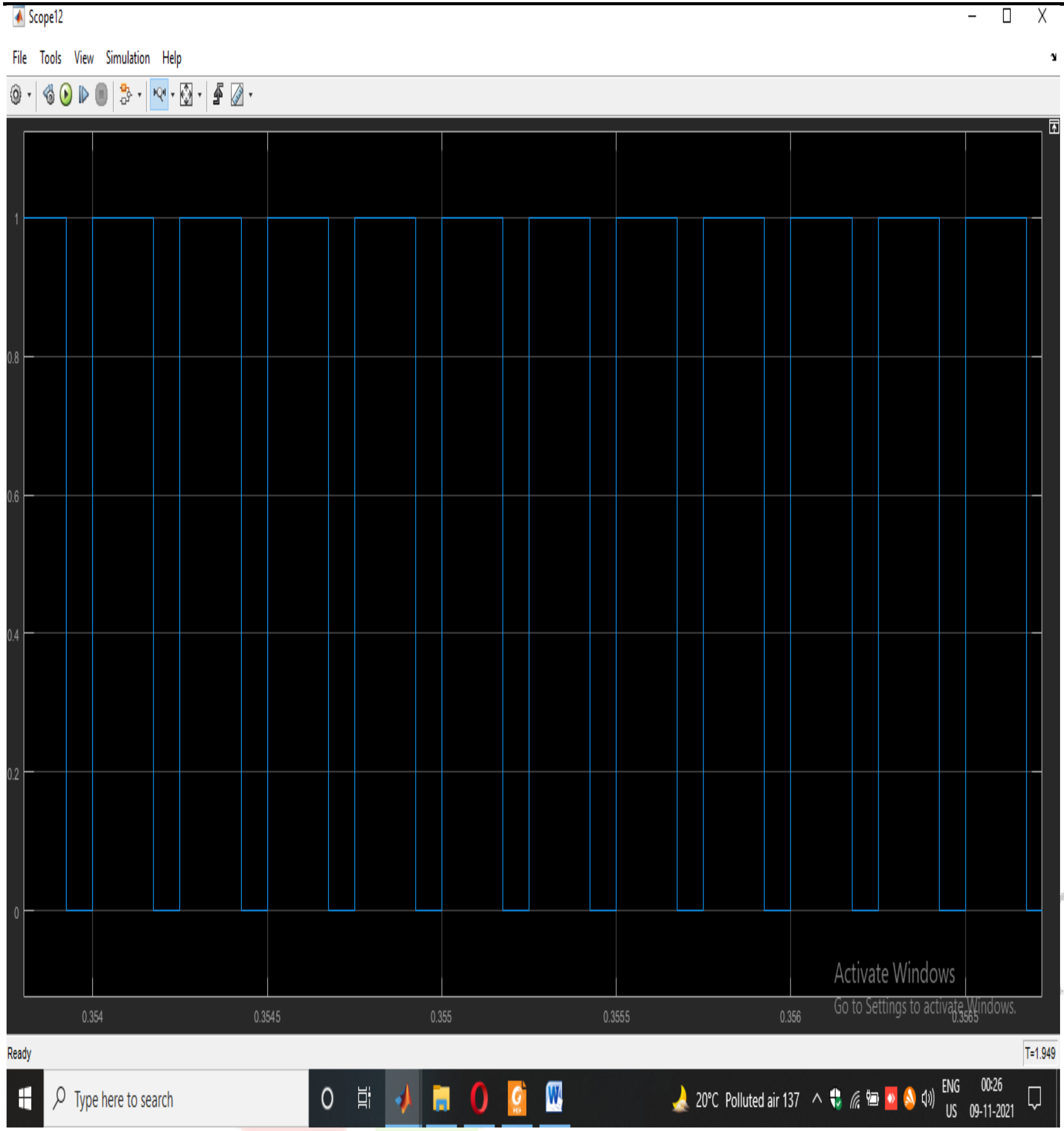
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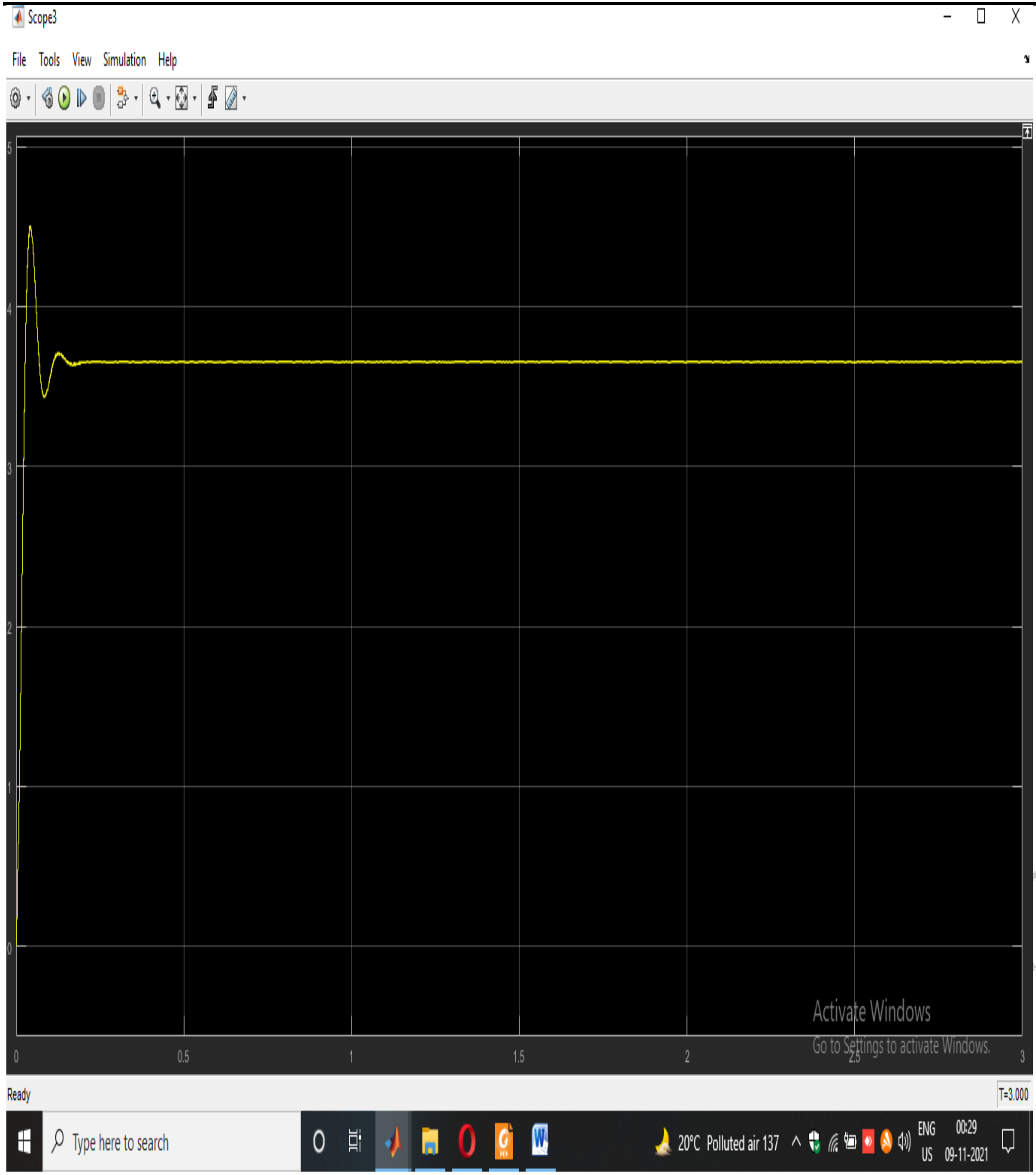
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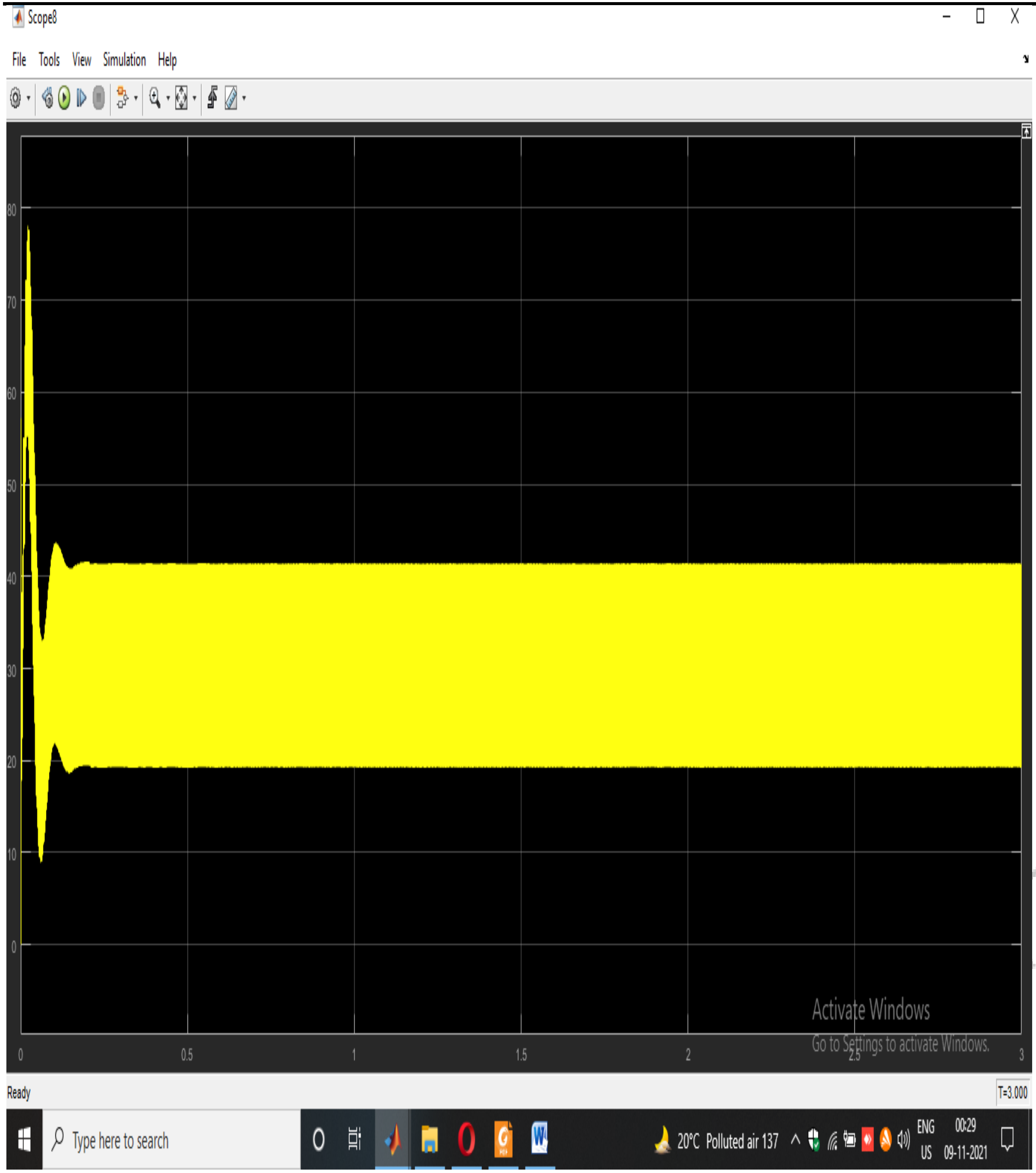
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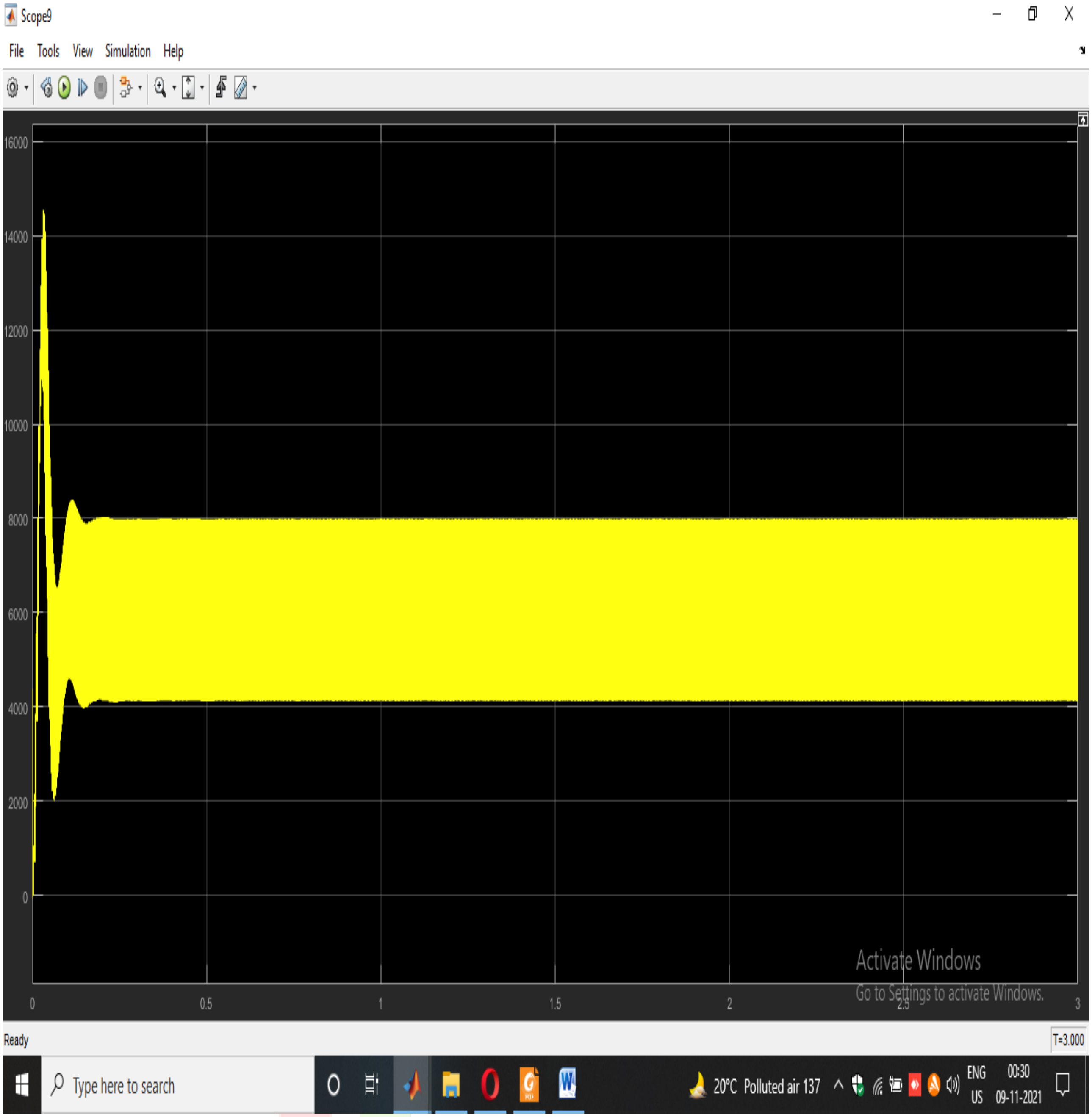
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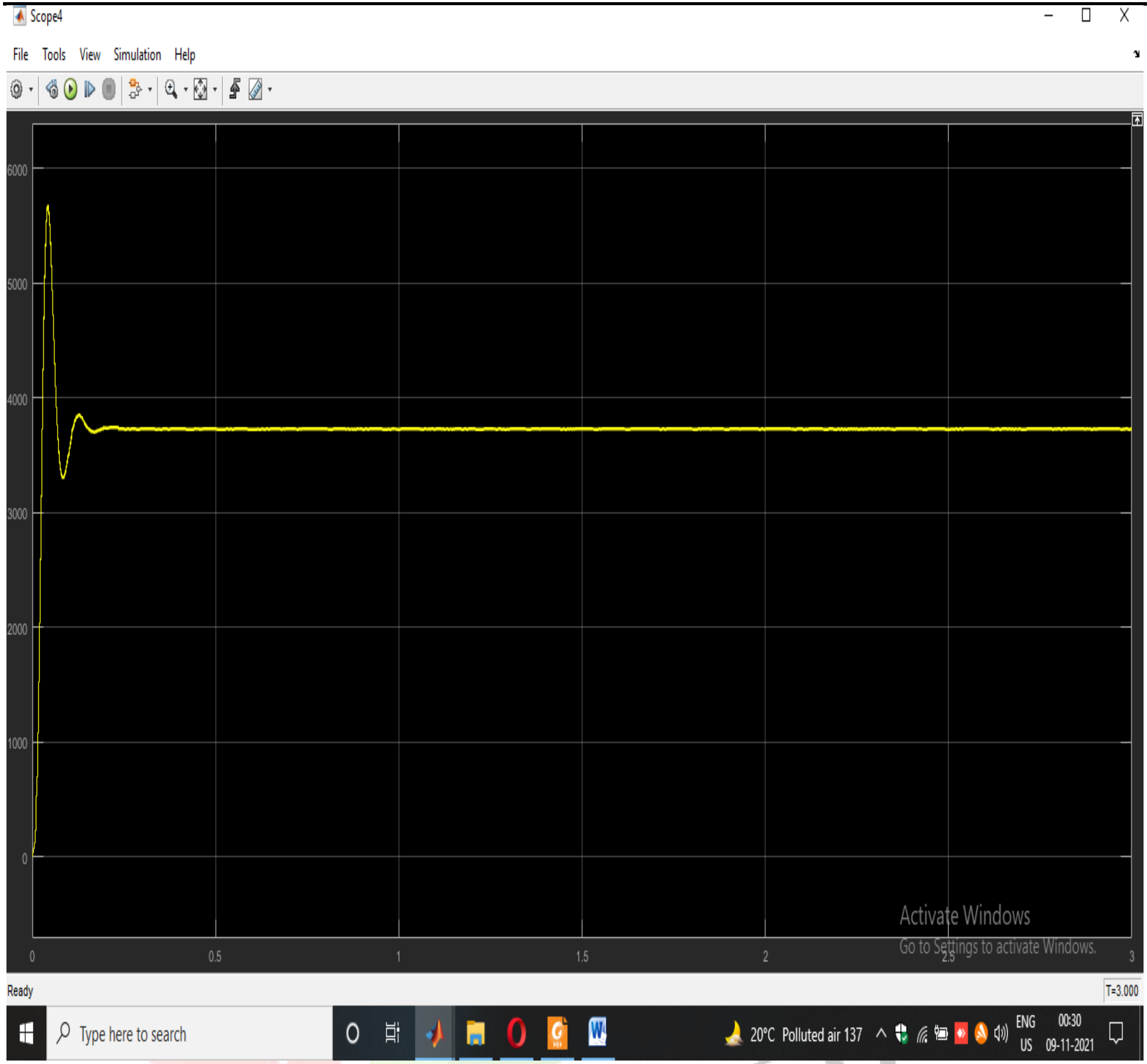
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CHAPTER-5

5.1 CONCLUSION

This paper presents a novel smart control of transmission line connected large PV solar system as a STATCOM, termed PV-STATCOM, for damping power oscillations and thereby substantially increasing the power transfer capacity of the network. The proposed control provides POD through reactive power modulation utilizing the entire inverter capacity during nighttime. During daytime the solar farm discontinues its real power generation function very briefly (about 15 sec) and utilizes its entire inverter capacity for POD. It subsequently restores power generation to its pre-disturbance level in a gradual manner while keeping the POD function activated utilizing the remaining inverter capacity. EMTDC/PSCAD simulation studies demonstrate the effectiveness of the proposed PV-STATCOM control in a single machine infinite bus (SMIB) system which exhibits local inertial oscillatory mode, two-area system which displays both local inertial and inter-area modes of oscillations, and the 12 bus FACTS power system which has multiple interarea modes of oscillations. In SMIB system, a 100 MW midline connected PV solar system increases the power transfer capacity by 230 MW, whereas in the Two-Area system a 100 MW PV solar system increases the power transmission limit by 200 MW. Moreover, the proposed power restoration technique keeping POD activated is more than 3 times faster than that specified by grid codes (without POD function). The temporary (about 18 sec) shutdown of real power production function for POD is not seen to cause any adverse impact on system frequency. The proposed PV-STATCOM provides 24/7 functionality of an equivalent STATCOM for POD at the same location. This PV-STATCOM is expected to be about 50-100 times lower in cost than an equivalent STATCOM as it utilizes the existing infrastructure (substation, bus-work, transformers, circuit breakers, protection systems, etc.) of a PV solar farm to transform it into a full scale STATCOM of similar size. The PV-STATCOM as an alternate FACTS device is expected to bring significant savings for utilities seeking to increase their power transmission capacity. It also opens a new revenue making opportunity for transmission connected solar farms to provide 24/7 STATCOM functionality at substantially lower cost. Implementation of this technology of course requires appropriate agreements among utilities, system regulators, solar farm developers and inverter manufacturers. The objective of this paper is to propose a novel control of a single PV solar farm as PV-STATCOM for power oscillation damping during day and night.

If the PV-STATCOM control is implemented on multiple PV solar farms in electrical proximity, the PV-STATCOM controls will need to be coordinated in a similar manner as coordination of multiple FACTS devices, and HVDC and FACTS devices [3,38, 41, 44-47]. The control coordination among multiple PV-STATCOMs will ensure that all the participating PV-STATCOMs will simultaneously provide power oscillation damping and concurrently return to normal operation after the oscillations are damped out. This control coordination requires detailed control design and system studies, which are outside the scope of the present paper.

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