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ENHANCING DYNAMIC VOLTAGE STABILITY IN RESILIENT MICROGRIDS USING FACTS DEVICES

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Abstract: This study aims to investigate the stability of resilient microgrids that use flexible AC transmission system (FACTS) devices. Microgrids are a popular way of integrating various distributed energy resource (DER) technologies into the distribution system. However, the use of electronic power converters (EPCs) to couple these DER technologies has created new operation challenges that could affect microgrid stability, reliability, and resilience. Induction motor-type loads (IMs) are dynamic loads that are commonly found in distribution grids and air conditioning (A/C) types of loads. These loads demand a lot of reactive power for correct operations. This high demand could lead to a phenomenon called fault-induced delay voltage recovery (FIDVR), which can cause problems with dynamic voltage stability (DVS). To address these challenges, this study proposes the incorporation of FACTS controllers, such as a static VAR compensator (SVC) and a distribution static compensator (DSTATCOM), into the microgrid as reactive power supply resources. This proposal includes designing, optimal location, and dynamic modeling of FACTS devices to enhance microgrid operation resilience.

***Index Terms* - Resilient Microgrids, Dynamic voltage stability, Fault-induced delay voltage recovery (FIDVR), FACTS, SVC, DSTATCOM.**

1. INTRODUCTION

In the recent decade, there has been a massive implementation of renewable energy sources (RESs) in power generation for several reasons. Environment-friendly nature is one of the main reasons along with the sharp decrement in fossil fuel availability, low generation cost, and reduction in power loss for long transmission lines. The demand for RESs in the form of distributed generators (DGs) originated the notion of Microgrid (MG). MG can be operated in parallel with the utility grid or autonomously (islanded). The classification of MGs can be done depending on the location, such as urban and remote MGs. Urban MGs are usually connected to the grid and become islanded during some disturbances; they are primarily situated in university campuses, communities, and industries. Conversely, some areas can have islanded MGs due to their remoteness, including oceanic islands and hilly regions. The demand for those areas can be fulfilled by importing costly fossil fuels, such as coal and diesel. However, energy production from diesel can threaten the environment's purity and restrain the economic progress of the communities. On the contrary, the integration of renewable energy can provide the security of sustainable energy at a lower cost. Moreover, under some agreements, such as the Paris Agreement (COP 21), islanding nations are focusing intensively on high infiltration of renewable energy. Therefore, remote MGs are increasing worldwide. Microgrids have received considerable attention in the past two decades, driven by global environmental issues, the need for energy access in remote communities, and the promise of increased system resiliency and reliability. As can be seen, the remote MG capacity surpassed the 1000 MW milestone at the end of 2015. Afterward, there has been a gradual rise in the installed MG capacity and earned revenue.

The decarbonization needs of the global electricity matrix, the growing increase in distributed energy resources (DERs) based on non-conventional renewable energies such as wind Power (WP) and solar photovoltaic (PV), together with the difficulties of access to electricity in remote communities have given rise to a new energy infrastructure paradigm called Microgrid (MG). MGs facilitate access and universality to electrical energy, and because of their inherent characteristics, they allow the integration of different DER technologies, as well as different types of static and dynamic loads (also called fixed and flexible loads, respectively). From the operation point of view, MGs can operate in two modes: connected to a distribution network or in isolated/ autonomous operation mode. The control schemes that govern the MGs are categorized into three levels or layers with different scopes of applicability: (i) primary control, coordinating the local control operation for each DER, and loads in the MG. It is based on the local measurements of those parameters necessary for managing, operating, and controlling the MG in fast perturbations; (ii) secondary control responsible for MG operation according to the mode of operation used, and (iii) tertiary control, which is the highest control level and associates the operation in terms of economic dispatch. It can also coordinate multiple MGs interacting with each other in a system, communicating requirements from the distribution network in a cluster of MGs. The high penetration of PV and WP DERs electrically coupled to the MG through electronic power converters (EPCs) may cause dynamic voltage instability (DVI) scenarios when the control schemes of these devices do not have Low Voltage Ride through (LVRT) features or support operating schemes which may allow dynamic voltage control. In comparison, when DERs are based on synchronous generation, their reactive power supply capacities are limited due to their capacity curve and their excitation systems which may lead to voltage instability problems, especially in isolated MGs. Concerning the load components, these can also cause problems with voltage control and stability in MGs. The massive connection of induction motors (IMs) represents a threat to dynamic voltage stability (DVS) when disturbances occur due to the deceleration and possible blocking of the IMs. These problems are the leading cause of the fault-induced delay voltage recovery (FIDVR) phenomenon and in extreme situations may lead to prolonged voltage instabilities and rapid collapses. The massive penetration of air conditioners (A/Cs) in recent years has been constantly increasing. These are dynamic loads by nature because their main components have one or more induction motors. The modeling of this type of dynamic load plays a crucial role when analyzing the occurrence of FIDVR events or, in turn, DVI. The flexible AC transmission systems (FACTS) technology has enabled the mitigation of critical problems related to the stability of bulk electric power systems. However, with the recent growth and positioning of MGs, new and different problems associated with voltage stability have arisen. 1.2 Motivation. Electrical energy from renewable sources is the most flexible and clean form of energy. In India, the renewable energy sector is under development and growing at a very fast rate. The power quality and reliability are still to be improved up to the standards. Nowadays, researchers & engineers are investigating the dynamic performance of Microgrids with DER’s, including the improvements achieved in the operation resilience of MGs, which FACTS technology can provide, operating in a coordinated mode with the DERs. The model of the electronic power converters associated with DERs technologies is performed with LVRT schemes, considering the reactive power support requirements in the presence of resilient disturbances.

1.1. RESEARCH OBJECTIVE

The paper aims to analyze the Dynamic Voltage Stability (DVS) in Microgrids (MG) by introducing two Flexible AC Transmission System (FACTS) devices, SVC and DSTATCOM, and operating them separately but under a primary centralized coordinated control scheme with the Distributed Energy Resources (DERs) that make up each MG. Furthermore, the study carries out a comparative analysis based on the dynamic performance of the FACTS devices to determine which response is better in terms of DVS. The paper presents the main investigations in the literature that address the incorporation of FACTS devices in MG, considering different approaches.

2. LITERATURE SURVEY

A literary review of the works and research that have been carried out in different areas related to this work is presented here. Firstly, the importance of modelling and load behaviour in MGs to identify and solve associated problems is addressed Residential air conditioning (A/C) loads have among their main components induction motors (IMs), which are generally low inertia machines that make electrical systems more vulnerable to short-term dynamic voltage instabilities under the presence of disturbances. Additionally, some studies have been reported in the literature to analyse the problems of loads in MG systems, which are mentioned, the study presented in [1] shows several models of dynamic loads in an MG. It shows that when unscheduled transitions of the MG to its island mode occur, depending on the dynamic load component, there are scenarios that present problems with voltage and frequency stability. In the same way, researchers in [2] examine the problem of voltage stability in a low-voltage distribution network. The electrical system in this work has IMs-type loads, for which they propose a dynamic model of a PV inverter operating with 3 control strategies, to provide dynamic voltage support. This allows for avoiding DVI in simple contingencies and with different levels of penetration of PV generation in the distribution network. Several DVI mitigation techniques have been proposed in the literature in case of contingencies. From these, those that propose load shedding and disconnection schemes stand out. For instance, in [3] it is described that the multiple connections of IMs cause voltage stability problems due to the relationship of dynamic coupling between the change of the IMs and the voltage supply of the system. As a possible solution to this problem, it suggested to gradually disconnect the IMs that make up the MG. However, these techniques are not considered in this research because load shedding contradicts the operational resilience capacity of MGs. In [4], a distributed voltage control scheme was proposed to supply reactive power through the inverters in stand-alone MGs with static loads; being this a vital study in this topic. However, the limitation of this work is that only steady-state voltage stability is addressed. Implementing this type of technology brings with it multiple benefits to improve the operability of Microgrids to avoid load shedding, improve stability margins, and suitably fit the operational requirements of the MG to enhance its resilience [5], [6]. DSTATCOM/STATCOM standout due to their fast-operating response to compensate for reactive power, improve voltage stability in dynamic and static states, avoid dynamic voltage oscillations, and control the voltage module. In this sense, some reported works that have considered the incorporation of these devices have been analysed. In [7], the incorporation of 3 SVC units in the presence of short circuits in a part of the electrical power system of Saudi Arabia is utilized to improve performance and prevent voltage collapse. Additionally, the improvements in the operational performance of the IMs with the operation of the SVC devices in such short-circuit situations are included. In [8] a dynamic optimization technique was used to obtain the optimal location and sizing of SVC devices in a real system in the USA, with the presence of A/C load characteristics, to improve the dynamic voltage performance under a large disturbance. Similarly, in [9] a day and night control algorithm was proposed for active and reactive powers in a bulk test power system made up of conventional generation, PV, and a STATCOM device to mitigate FIDVR that meets and exceeds satisfactorily the requirements of the German network code In [10], reactive power and voltage stability performance in the incorporation of an SVC and STATCOM in an MG test system that has a doubly fed induction generator (DFIG)- based wind farm was comparatively analysed. In the study developed, a sensitivity index was proposed by which a STATCOM can be located in a distribution system, whose objective is to improve the voltage profile for the maximum use of the DER in case of single-phase faults [11]. In the work proposed in [12], it is presented an interesting dynamic control mechanism of voltage source converter type DERs. It is also used for hybrid generation systems (WP and PV) including a current source converter topology added to a super capacitor for smoothing the voltage ripple in the converter and therefore the harmonics content in the distribution network. This research represents novel control mechanisms of applicability to Microgrid systems.

2.1. SUMMARY

An overview of recent literature on Enhancing Dynamic Voltage Stability in Resilient Microgrids Using FACTS Devices has been discussed and identified common aspects in each of the reviewed papers. This allows identifying directions for further research.

3. PROBLEM STATEMENT

Control solutions to mitigate slow voltage recovery problem can be broadly classified into two parts
i) Supply side solutions
ii) Demand side solutions.

Demand side solutions use the protection system to rapidly disconnect motor loads during periods of low voltage, and there are different strategies to limit the amount of load affected by the low voltage problem.

Supply side solutions focused on containing and mitigating Fault Induced Delayed voltage recovery (FIDVR) events

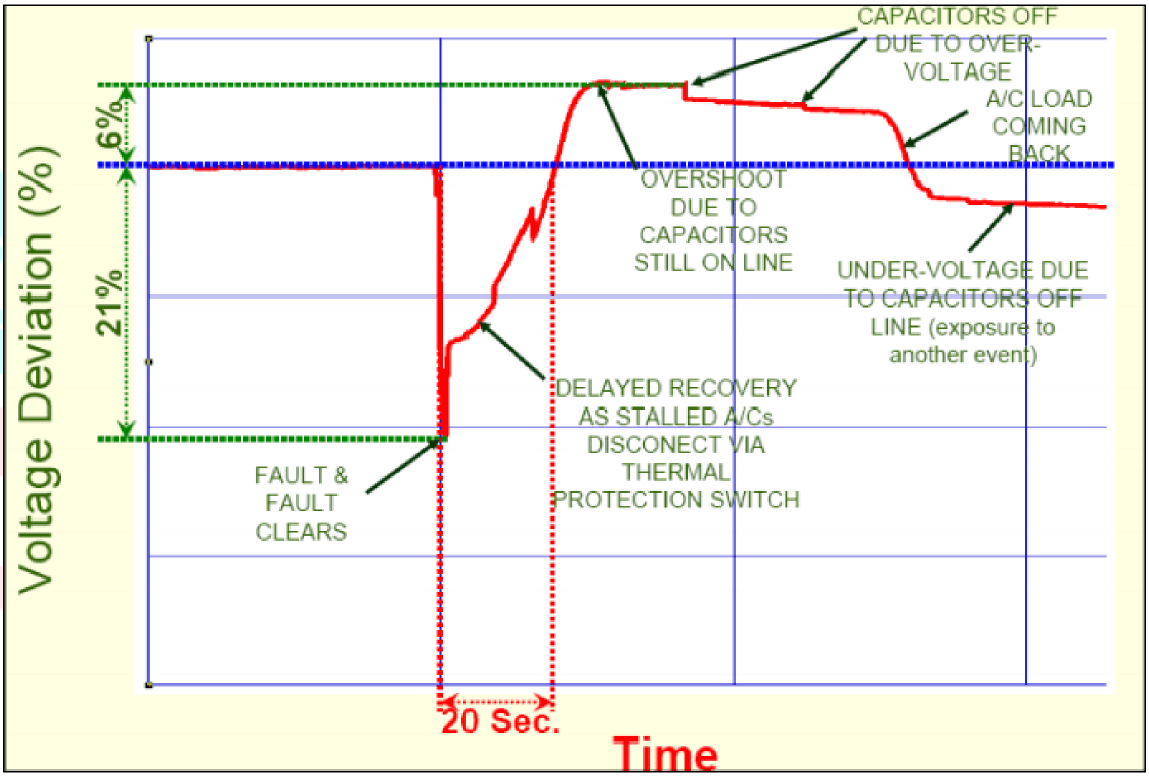

Figure - Fault induced delayed voltage recovery (FIDVR) event

Large-scale installation of these devices is expensive, and their cost increases with size (capacity). The effectiveness of dynamic support is dependent on its location. Therefore, it is necessary to develop dynamic VAR placement strategies that enhance short term voltage stability and at the same time remain cost effective solutions. Based on the bibliographical review carried out, it is evident that there is a lack of significant contributions regarding the evaluation of dynamic voltage stability analysis in Microgrid systems experiencing simultaneous contingencies of resilient nature. These contingencies, although having a low probability of occurrence, can have significant operational impacts. Furthermore, while international grid codes and the IEEE-1547-2018 standard permit power electronic converters associated with DERs in MGs to operate in smart mode, there remains a considerable deficit of reactive power when this type of generation is affected by resilient faults. This deficit hinders the ability to maintain stability and operability of the system, particularly with high penetration of dynamic loads. Moreover, there is a notable absence of a comparative analysis regarding the utilization of FACTS devices in shunt connection to address these DVS and resilience issues in MGs. Consequently, no metric or index has been developed to quantitatively evaluate a resilient event of type N-1-1, thereby quantifying the operational resilience of electrical Microgrids following contingencies. As a result, there exists a significant gap in addressing the close relationship between dynamic voltage stability and operational resilience in electrical Microgrid.

4. DYNAMIC VOLTAGE STABILITY ANALYSIS

In traditional electrical power systems, synchronous machines are the predominant generation systems. These machines have well-defined controllers that effectively regulate the active and reactive power flows under normal and contingency conditions. An intrinsic characteristic of synchronous generators is their heavy rotor, which provides significant inertia for avoiding instabilities caused by sudden changes in rotor speed during disturbances. However, DERs integrated into Microgrid systems through electronic power converters lack inherent inertia due to their construction characteristics. As a result, control strategies and algorithms have been developed to provide virtual inertia, enabling control and management of active and reactive power. Nevertheless, these DERs face limitations associated with the intermittent nature of their primary energy sources, either solar radiation or wind in the case of the PV and WP generations, respectively. When DERs integrated through EPCs constitute the majority of generation in a Microgrid, the challenges related to maintaining dynamic voltage stability become more complex during Microgrid isolation. This is primarily due to the deficit in supplying reactive power, which is essential for maintaining system operability. Therefore, DERs must be equipped with support and dynamic control schemes that enable the provision of reactive power during fault conditions, intending to secure the operability of the MG, ensuring the stability and reliable operation of the Microgrid. Dynamic voltage stability in Microgrids can be defined as the system‟s ability to restore its permissible operating voltage level within a short timeframe after the occurrence of contingencies (or disturbances). In particular, the DVS also called short-term voltage stability is an analysis that is conducted in the time domain framework, focusing on a short-range scale typically up to 5 sec. additionally, to analyse the dynamic voltage stability, it is crucial to accurately model the dynamic behaviour of loads. Similarly, when considering short-duration faults located in close proximity to loads, understanding their impact on the Microgrids performance and dynamic response becomes a primary concern. Furthermore, the relationship between the dynamic voltage stability (DVS) and the hierarchical controllability scheme of the Microgrid is significant. This scheme encompasses the coordinated primary control system among DERs components and FACTS devices. This coordination plays a pivotal role in the analysis of the Microgrid operational resilience, representing a critical aspect to be addressed.

4.1. PERFORMANCE INDICES FOR DYNAMIC VOLTAGE STABILITY ANALYSIS IN MICROGRIDS

4.1.1. VOLTAGE DEVIATION INDEX (VDI)

This index relates the deviation of the voltage module i of the discretized signal at instant t concerning the voltage module in pre-fault conditions, which has been considered to be 1.0 p.u. Expression (1) shows the mathematical calculation relationship for this index. It is necessary to clarify that, if the DVI_j^k is closer to 0 p.u., this will represent better post-disturbance voltage performance; otherwise, when it is closer to 1.0 p.u., it indicates poor dynamic voltage performance and it can be interpreted as a dynamic voltage instability scenario.

$$DVI \int_j^k = \sum_{Vi\epsilon\beta} . \sum_{t\epsilon T} . \frac{|1.0 - Vi,t|}{N_N . N_s}$$

(1)

Where j and k are the types of faults and FACTS devices node location in the MG respectively. Vi Represents the voltage magnitude in the sample space of the voltages to the simulation signal for timeti, and NN is the number of nodes and NS is the number of samples in the discretized signal.

4.1.2. DYNAMIC VOLTAGE PERFORMANCE INDEX (DVPI)

Ideally, the voltage behaviour as a function of time when there is no fault in the MG shows a voltage level close to 1.0 p.u. at all times. A different situation occurs when the system subjected to a disturbance. In that case, the transient dynamics of the process causes distortions in the system voltage. The analysis carried out to determine the dynamic voltage performance index (DVPI) is calculated using

$$DVPI \int_j^k = \frac{1}{N} \sum_{ti=0}^{T} . \sum_{i=1}^{\beta} . [\Delta ti . |Vi|]$$

(2)

Vi Represents the voltage magnitude of the simulation signal for time ti, represents the total number of discrete voltage magnitude samples in the analysed time window T, and NN is the number of nodes. When DVPIjk is closer of the pre-fault voltage and the time T, which corresponds to the analysed time window, the MG has a better performance in terms of dynamic voltage response. For example, for the studies cases of this work, in stable conditions without the presence of faults in the MG and for a time window of 5 s with ti=0.001, the DVPI would be equal to 5 (since 0.001.5000=5).

4.1.3. TRANSIENT DYNAMIC VOLTAGE SEVERITY INDEX (TDVSI)

To quantify the voltage dynamic behaviour during and after the fault that caused the MG isolation, it is introduced a mathematical expression that allows evaluating and determining the performance in terms of DVS. The transient dynamic voltage severity index (TDVSI) is presented in (3), which was adapted from [44] and modified for the analysis in MGs.

$$TDVSI \int_j^k = \frac{\sum_{i=1}^{N} \cdot \sum_{t=Td}^{T} \cdot [|Vi,t - Vi,0|]}{N_N (T - Td)}$$

Where i represent different MG nodes, NN is the number of nodes. Vi, t is the node i voltage magnitude at time t obtained from the dynamic simulation in the time domain, Vi,0 is the voltage magnitude in pre-fault conditions, Td and T represent the fault clearance time and the time of the analysis window in the simulation process, respectively. Lower TDVSI j to k value indicates a better transient voltage performance.

4.2. IMPACT ON THE VOLTAGE STABILITY

In this section, the impact on the voltage stability is discussed. In the grid-following control, the main objective is to inject the reference current to the system. These reference current components at normal operating condition. Thereafter, the state equations of the inverter circuit with filter. The current controllers using two PI controllers are designed to obtain the modulation signals. On the other hand, in the grid forming controller the current in both of the inverter controls, grid following and grid forming, these equations are analysed to define the stability region of the controller itself. Since, this research is mainly focused on the inverter dominated islanded MG, the deviation from the stability region of the inverter controller consequences uncontrolled supply to the system which significantly impacts on the voltage stability during disturbances. The diesel engine operates as master unit by providing the reference voltage and frequency to the system. To maintain the terminal voltage, the diesel engine governor and excitation systems are designed. If diesel generator does not operate in stable condition, the system experiences an unstable operation with deviated reference voltage and frequency. Hence, the stable operation of the diesel generator as a master unit is very crucial to maintain the dynamic voltage stability of the system. Finally, load modelling which is very significant for dynamic voltage stability assessment. Specially, the IM load as dynamic load plays a vital role in the dynamic voltage stability since IM operates in stalling mode during low voltage condition. To obtain a realistic operation, a fourth order state space model of IM load is developed with equivalent electrical and mechanical systems. The demanded extra power during stalling mode is one of the major reason for the dynamic voltage stability issues. Since the stalling mode of the IM load is one of the main reasons for dynamic voltage instability, the proper dynamic modelling is conducted so that IM can maintain the stability during stalling mode which can resist any other adverse impact on dynamic voltage stability. 4.4.

4.3. SUMMARY

In this chapter the Performance Indices for Dynamic Voltage Stability Analysis in Microgrids, general configuration of DERs integrated into Microgrid systems through electronic power converters lack inherent inertia due to their construction characteristics, and Overview of Impact of the modelling on the voltage stability.

5. RESILIENT MICROGRIDS

At present, electric power systems are taken a unique technological path that is driving the development of a novel energy paradigm. New energy sources of non-conventional renewable energy (NCRE) have allowed the positioning of distributed generation (DG) and electrical Microgrids (MGs) systems to shorten the accessibility gap to electric power worldwide. Research and development on power electronics- based devices and their integration into electric power systems (EPSs) have allowed improving the operating conditions in stationary and dynamic states. MG systems, due to their topological and infrastructure conditions, require specific mechanisms to optimize their operation. In this sense, the Microgrid resilience has emerged as topic of major concern which requires further development, especially considering the potential of power electronics to improve the dynamic behaviour of modern electricity systems. Thus, this work focuses on studying the benefits and applicability of modern flexible ac transmission system (FACT) technology in distributed generation and MG systems aiming to improve their resilient operation. The concept of MGs dates back to 1882 when inventor Thomas Alva Edison built his first power plant in the United States. Edison´s Company installed 50 dc MGs over a period of four years.

Later, in the late nineteenth and early twentieth centuries, with the increase of large generation centres and transmission lines encouraged by economies of scale associated with continuity and reliability of supply, EPSs became a monopoly service. Nonetheless, in the last years of the current century, a new trend has emerged around the world to deploy Microgrid systems. This tendency is justified by the need of efficiently supplying an increasingly electricity demand, recent advances in power electronics, the rise of a new distributed energy resources (DERs) and the requirement of a greater coverage, reliability, power quality and resilience. Thus, this paper focuses on providing a thorough study of this latter issue and the applicability of flexible ac transmission systems (FACTS) technology to improve the MG operating resilience.

The U.S. Department of Energy (DOE) defines the MG as a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A Microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island (autonomous) mode. On the other hand, CIGRÉ defines the MG as electricity distribution systems containing loads and distributed energy resources (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.

5.1. MAJOR ISSUES OF MICROGRIDS

A major problem in MGs with high penetration of NCRE- based DERs are the continuous voltage fluctuations, especially in islanded operation. These fluctuations are usually caused by temporary power injections. Additionally, power fluctuations must be considered due to the inclusion of photovoltaic (PV) arrays, wind turbine (WT) parks and energy storage systems (ESSs) connected as part of MG system. The inclusion of NCREs becomes more challenging the power control of the Microgrid because of the increased intermittency and uncertainty which makes difficult to maintain generation-demand balance at all times. Major features of MG systems include bidirectional power flows, the variation of the voltage profiles within the established ranges, uncertainty in the generation of electricity and variations of electric demand scenarios.

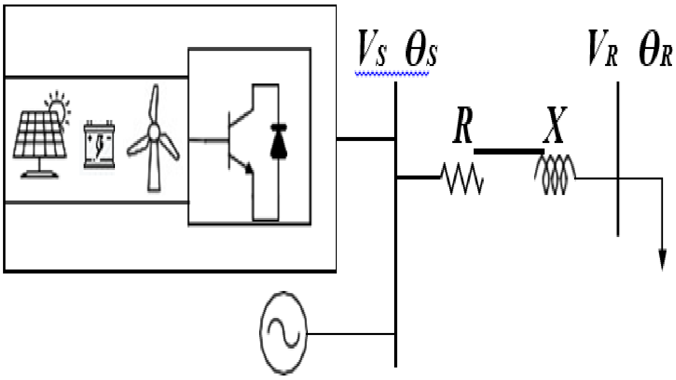

Figure 5.1: Power Flow between two buses in a Microgrid

To solve these issues, multiples actions are required in terms of the response of mechanisms and strategies of the control systems. On the other hand, the strong coupling between voltage and frequency in Microgrids further complicates the frequency control (or regulation). This happens due to the high R/X ratio of feeders making up the MG, so it is not valid to consider the mathematical decoupling in formulating active power flow and voltage magnitude, as usually made in classical electric studies. Within this context and, due to the relatively small size in terms of MGs power, variations in voltage at DER terminals will be reflected almost instantaneously at the system load buses, which cause a change in the demand of the system that will act according to the voltage stability indices. Therefore, coupling between voltage-frequency electrical variables must be taken into account in the stability analysis and the frequency control of MGs.

Topological structures of weakly meshed electrical grids become highly vulnerable to the occurrence of disturbances that could cause high transient and dynamic problems with high probability. Operation security together with economy is the main topics to be considered in the operation of EPSs and in present times particularly in DG and MG systems. This requirement can be stated as maintaining control of voltage and frequency, monitoring thermal limits and/or stability on different branches and buses, limiting short-circuit currents at different buses and complying with security criteria for possible failures. Operation security can be defined as the capacity of the electric system to continue in operation at any given time in the case of a sudden out of service of any DER components comprising the MG. The new approach currently being considered is the ability of MGs to guarantee its resilient operation, especially when loads are critical and require a continuous and reliable energy supply. In Fig. 1, the connection of several DERs in an MG system is shown schematically. It is to be noted that according to the resistance and reactance characteristics of the feeder, the parallel capacitance is negligible in MGs.

5.2. DISTURBANCES IN MICROGRIDS

As in the case of large power systems, in Microgrids, a disturbance is considered small if a set of linearized equations can adequately represent the behaviour of the system. Small disturbance stability refers mainly to sustained oscillations that arise from a critically damped system response to a small disturbance. Depending on the root cause, small disturbance instability can be a short or long term phenomenon. To quote an example, poor coordination among DERs in the power distribution system may produce undammed power swings that could grow rapidly beyond the acceptable ranges or limits of operation in the short term. It is important to note that the planned isolation process of a Microgrid produces much less significant frequency and voltage deviations in the system than when it is unplanned. This happens since the operating points of DERs are calculated and adjusted considering the MG operation in island mode. When this transition occurs, one of the DERs of the island must be operated in frequency regulation, load tracking, and grid-forming modes. The time lag involved in this transition may take some cycles if it adds to the complexity of maintaining the stability of the MG. This is particularly a problem when the isolation is not planned, the MG does not have or has little inertia and, the exchange of power with the distribution network before disconnection is large (for example 50% of the Microgrid local demand). In this case, voltage sags and swells may appear within a few cycles that could compromise the inverter security, which would cause the islanded MG to become rapidly vulnerable or in the worst case to be unstable. In the context of MGs, major disturbances included are short circuits, unplanned transitions from grid-connected to islanded (autonomous) mode of operation, and the loss of distributed generation units. These disturbances can cause large frequency and voltage deviations and also power oscillations between the multiple DERs forming the MG system. The above-mentioned problems can be caused by numerous reasons, such as a critical system oscillation mode being pushed to the unstable region by a fault, producing undammed oscillations in the system. A similar behaviour may be observed during an unintended islanding of a grid-connected Microgrid. Therefore, appropriate power coordination among DERs and adequate response time of their controllers are critically significant to maintain system stability. In terms of the time frame, stability problems due to large isturbances in MGs can be classified as short-term phenomena, that is, in the order of a few seconds. Therefore, it is necessary to have support equipment that allows the correct operation of the MG and above all with very short response time.

5.3. FLEXIBLE AC TRANSMISSION SYSTEMS (FACTS)

The concept of FACTS was proposed in 1986 to provide stability and increased power handling capacity by the injection of reactive power using electronically controlled elements connected either in series or in parallel with the lines. Recent research and developments in this technology have resulted in improving real-time control performance, such as reactive power injection/absorption; thus providing opportunities for voltage and frequency control, and enhancing stability in power systems and particularly in MGs. All this, associated with the typical very short response time of the power electronic devices. Taking into account the architecture and power electronics components, FACTS are based on a wide range of devices and equipment, such as dc/dc converters, dc/ac converters, etc. These systems contain power switching semiconductor devices arranged in various topologies, which introduces complexity to the dynamic modelling of the systems. Multiple types of FACTS controllers have been developed for compensation of different EPS parameters. However, static power converter (also called inverter)-based controllers are the main concern for MGs since they have an enhanced dynamic control capability. Compared with thyristor-based compensators, converter-based compensators have the features of fast response, continuous regulation, multiple functions, smaller physical size, etc. These converters can be built using two types of sources: voltage and current sources. A voltage source converter (VSC) operates by imposing a stiff voltage at the dc link regardless the current flowing through it (generally using a capacitor). In contrast, a current source converter (CSC) operates by imposing a current at the dc link regardless of the voltage at its terminals (usually using an inductor).

Despite their structure differences and applications, both can regulate the current and voltage, with single or multiple application control loops. Multiple benefits and functionalities can be identified for deploying FACTS technology and especially for impacting the resilience of distribution systems with a view towards a smarter energy network. They include, among others: i) to increase the penetration of NCREs; ii) to improve power transfer capacity; iii) prevent and reduce loops flows; iv) to achieve rapid controls in dynamic events for voltage and frequency regulation/control; v) to balance power flows in parallel power networks to avoid under loading/overloading of grid components; vi) to improve the stability margins in terms of voltage, frequency and transient stability; vii) to provide greater flexibility for the installation and location of new DER generating plants in MGs systems or modifications in MG island operating mode. On the same way, some key benefits of RACDS in a smart grid include: (a) to make easier the interconnection between feeders to improve grid resiliency; (b) to enable and increase the penetration of distributed generation sources; (c) to use energy storage systems and voltage restorers to provide fast dynamic voltage and frequency support in case of emergency/blackouts and voltage sags due to sudden variation in the source/load profile; (d) to mitigate power quality issues so as to ensure reliable power supply to critical loads; and (e) to allow increasing penetration of electric public transportation (electric cars, underground rails, etc.) in the distribution network. FACTS devices can also be used to provide backup power and frequency control for EPSs. In addition, they can improve voltage stability in the point of common coupling (PCC), by providing voltage support/regulation.

Moreover, FACTS technology can assist during the restoration process of power systems in case of faults and thus allow to avoid cascade blackouts. Due to their reactive power injection capacity, they also help to increase the power transfer capacity, improving the use of the network assets, and the margins of voltage stability and dynamic system stability performance. In DG, the decision of power injection of the DERs composing a MG will depend on the control actions of its components, which is currently a relatively unexplored area in relation to the topic of voltage stability in MGs that have an island operation mode or that are in the MG operation mode. In some applications, like the one this thesis work is researching, it is necessary to be able to push current in both directions. For example, in an electric powered vehicle where the converter has to be able to run in motoring mode where it powers the motor and generator mode where it's charging a battery pack. This can be achieved by combining a buck converter and a boost converter. The result is a two-quadrant buck-boost converter that can operate either in buck mode or boost mode depending on the situation.

5.4. DSTATCOM

Basically, the DSTATCOM system is comprised of three main parts: a Voltage Source Converter (VSC), a set of coupling reactors and a controller. The basic principle of a DSTATCOM installed in a power system is the generation of a controllable ac voltage source by a voltage source inverter (VSI) connected to a dc capacitor (energy storage device). The ac voltage source, in general, appears behind a transformer leakage reactance. The active and reactive power transfer between the power system and the DSTATCOM is caused by the voltage difference across this reactance. The DSTATCOM is connected to the power networks where the voltage-quality problem is a concern. 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 to drive the main semiconductor switches (IGBT's, which are used at the distribution level) of the power converter accordingly. The AC voltage control is achieved by firing angle control. Ideally the output voltage of the VSI is in phase with the bus (where the DSTATCOM is connected.) voltage. In steady state, the dc side capacitance is maintained at a fixed voltage and there is no real power exchange, except for losses. The DSTATCOM differs from other reactive power generating devices (such as shunt Capacitors, Static VAR Compensators etc.) in the sense that the ability for energy storage is not a rigid necessity but is only required for System unbalance or harmonic absorption

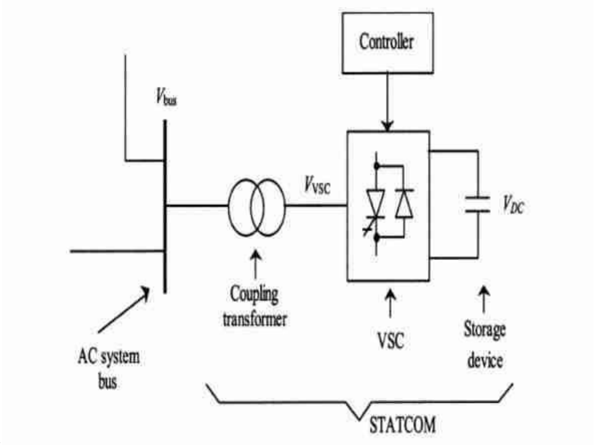

Figure 5.4: Block Diagram of the voltage source converter based DSTATCOM

There are two control objectives implemented in the DSTATCOM. One is the ac voltage regulation of the power system at the bus where the DSTATCOM is connected. And the other is dc voltage control across the capacitor inside the DSTATCOM. It is widely known that shunt reactive power injection can be used to control the bus voltage. In conventional control scheme, there are two voltage regulators designed for these purposes. AC voltage regulator for bus voltage control and dc voltage regulator for capacitor voltage control. In the simplest strategy, both the regulators are proportional integral (PI) type controllers.

5.5. STATIC VAR COMPENSATOR (SVC)

Static VAR Compensator (SVC) also known as Static Reactive Compensator is a device used to improve the power factor of an electrical power system. It is a type of static reactive power compensation device that is used to inject or absorb reactive power into or out of the system to maintain a desired voltage level. An SVC is a part of FACTS (flexible AC transmission system) and consists of a bank of capacitors and reactors, which are controlled by power electronics such as thyristors or insulated gate bipolar transistors (IGBTs). The power electronics can rapidly switch the capacitors and reactors on and off in order to inject or absorb reactive power as needed. The control system for the SVC monitors the system voltage and current and adjusts the reactive power output of the device accordingly.

SVCs are generally used to compensate for fluctuations in reactive power caused by changes in load demand or changes in generation, such as the output from wind or solar power sources.

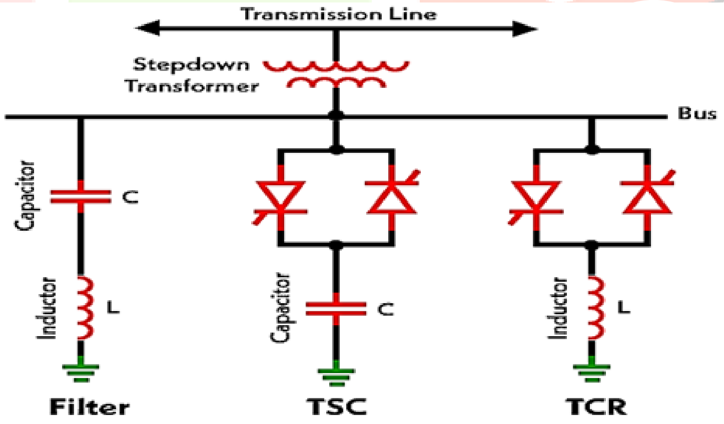

Figure 5.5: Block Diagram of the SVC

The SVC works by injecting or absorbing reactive power into the power system in order to maintain a constant voltage and power factor at the point of connection.

An SVC (Static VAR Compensator) is an electrical device used to regulate the voltage and reactive power (VAR) in electrical power transmission and distribution systems. It is a type of static compensator that uses power electronics to control the voltage and VAR on the electrical grid.

The SVC consists of a thyristor-controlled reactor (TCR) and a thyristor-switched capacitor (TSC). The TCR and TSC are connected in parallel with the power transmission line. The TCR is used to control the inductive reactive power and the TSC is used to control the capacitive reactive power. The combination of the TCR and TSC allows the SVC to quickly and accurately inject or absorb reactive power to maintain a desired voltage level and improve the power factor of the system.

The SVC continuously monitors the voltage and current in the power transmission line and adjusts the reactive power injection or absorption based on the voltage level. If the voltage level drops below the desired level, the SVC will inject reactive power into the system. Conversely, if the voltage level rises above the desired level, the SVC will absorb reactive power from the system.

The TCR and TSC are typically connected in series with a common DC bus, which is controlled by the control system. The control system adjusts the firing angle of the thyristor devices to regulate the reactive power injection or absorption by the TCR and TSC. The combination of the TCR and TSC allows the SVC to quickly and accurately inject or absorb reactive power to maintain a desired voltage level and improve the power factor of the system.

By injecting or absorbing reactive power as needed, the SVC helps to maintain a stable voltage level and improve the power factor of the system. This helps to reduce losses in the system and improve overall system efficiency.

6. FUTURE SCOPE

The areas of application of STATCOMs in the operation and control of a power grids are erroneous. It is used in schedule of power flow, reduction in the quantity of unsymmetrical components installed to damp power fluctuations. In addition, it support the stability of transient in the system. When compensators are in operation, at times of generation shortfall or network constraint, the voltage of the non-critical loads is reduced while regulating the voltages across the critical loads. This addresses the generation shortfall or network constraint and also facilitates better voltage regulation of the critical loads through manipulation of the supply impedance voltage drop[8].The relevance of the STATCOM when in operation is majorly to control the power system dynamics. This is achieved by providing a damping against power system oscillations. It equally extends to the damping of sub synchronous oscillations with the aim of providing balance in loading of individual phases. STATCOM also improve the transient stability margin and steady-state power transfer capacity. Reduction in temporary over-voltages, Effective voltages regulation and control. Reduction of rapid voltages fluctuations were among other uses of the STATCOM. In addition, an Energy Storage System offers the following distinct advantages:

a) Provide system damping, while maintaining constant voltage following a disturbance.
b) It could control both active and reactive power simultaneously and independently.
c) It could charge batteries by absorbing active power from the grid.
d) It was rated higher because of multilevel topology.
e) It is capable and effective of damping the power oscillation.
f) It supports the system voltage during and after a disturbance.
g) Provide additional damping in situations where the dynamic reactive power provided by traditional FACTS controllers with similar ratings are inadequate.
h) Alternatively, it could provide the same amount of damping at less cost. Damping of oscillation, by repeatedly interchanging small amounts of real power with the system, would be an excellent ESS application.
i) Provide energy to maintain the speed of locally connected induction motors during a power system disturbance. This may prevent a voltage collapse in areas where there is a large concentration of induction motors that would otherwise stall.

More reactive power compensation installations are probably required in the near future to overcome system limitations which is seen an important contribution to increase system stability and prevent blackouts. For a given range of supply voltage variation, the total voltage regulation and the total reactive capacity required for each option to produce the desired voltage regulation at the point of connection are expected to be better. The future holds that advancement may require less overall reactive power capacity than STATCOM and yields better total voltage regulation. This makes energy storage system (ESS) a promising technology for future smart grids where selective voltage regulation for sensitive loads would be necessary alongside demand side response. Further it is stated that the energy storage technology will be the key to the future development of renewable energy. In some of the commercial successes in electric power storage technologies have been discussed and it also discusses some of the emerging applications in power storage like wind farm power stabilization, etc. A catalogue of the various current technologies (steam, hydro, wind, etc., and storage being one of them). Their future outlooks, evaluations of security of supply and environmental impacts, climate change evaluations, and technical and economic analysis, in the context of energy planning activities.

7. CONCLUSION

The impact of FACTS devices in order to improve the dynamic voltage stability in resilient Microgrids has been analysed and investigated. The different case studies and scenarios considered were carried out in a reference test MG system and in the actual Microgrid system of the Galapagos Islands in Ecuador. Nevertheless, it was demonstrated that, with a control scheme for solar PV and wind DER inverters, based on the IEEE-1547-2018 standard operating in coordination with the FACTS either SVC or DSTATCOM, significant improvements in performance and dynamic voltage stability are obtained even mitigating completely the FIDVR in all scenarios and circumstances analysed. Regarding the determination of the optimal nodal location in the connection of the FACTS in the MG, the different resilient contingencies in the feeders and interconnection link to the grid were considered.

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