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A CONTROLLER IMPROVING PHOTOVOLTAIC VOLTAGE REGULATION IN THE SINGLE-STAGE SINGLE-PHASE INVERTER USING IOT

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ABSTRACT

While substantial research covers current control and synchronization of grid-connected photovoltaic (PV) inverters, issues concerning control of the PV input voltage deserve more attention, as they equally affect the reliable and stable operation of the system. Hence, this article analyses the PV voltage regulation in the single-stage single-phase PV inverter. In contrast to previous work, the PV source influence on the input voltage dynamic is analytically formalized, exposing a potential instability when the PV source is operating in its constant current region. A traditional proportional-integral PV voltage controller fails to ensure a consistent and stable voltage regulation. On the other hand, this issue is resolved by the proposed feedback linearization based controller. The new controller is validated on a test setup comprising of a PV source emulating a 1.2 kW PV array, interfaced to a single-phase inverter connected to a grid emulator. Confirming the issues predicted by the theoretical analysis, the experiments prove two main advantages of the proposed controller. First, PV voltage regulation instability is eliminated when the PV array operates in its constant current region. Second, the PV voltage transient behavior is now independent of the operating point of the PV source.

Keywords: Renewable energy, PV modules and PWM switching.

1. INTRODUCTION

The penetration of renewable energy sources is increasing exponentially due to power and digital electronics. Renewable energy sources are connected to the grid through power converters which besides transferring the generated dc power to the ac grid. The grid connected Photovoltaic (PV) systems are essentially composed of arrays of PV modules, connected to the grid through a power conditioning system includes a DC/AC converter, the Maximum power point Tracker MPPT, the filter and the control systems needed for performing efficient system operation

The control tasks can be divided into two major parts [1–5].

The controller on the PV modules side, is used in order to extract the maximum power from the PV modules

The controller on the grid side, is used in order to control both active and reactive power supplied to the grid;

Control of dc-bus;

Guarantee high quality of the injected power;

Grid synchronization.

For lower installation of photovoltaic systems connected to the grid, pulse width modulation (PWM) is a widely used technique for controlling the voltage source inverters injects currents into the grid. The current injected must be sinusoidal with reduced harmonic distortion. Moreover, a sinusoidal input current should be achieved with a total harmonic distortion (THD) below 5% as suggests the international standard IEEE std 929 — 2000. The main objective of the current controller is to ensure that the output inverter current follow carefully the reference current independently of the selected control technique. The current controller of power converters can be a closed loop PWM, such as Hysteresis Current Control, linear PWM, predictive controllers, optimized controllers, neural network and fuzzy logic controller systems. In comparison to open loop, PWM techniques, have several considerable advantages, such as extremely good dynamics, instantaneous peak current control and prevention of overload and pulse dropping problems. For grid connected photovoltaic single phase inverter; there are two common switching strategies, which are applied to the inverter; these are Bipolar and Unipolar PWM switching. The PWM technique could be utilized for controlling the inverter's voltage source that injects currents into the grid. Many PWM procedures can be adopted. Generally, the PWM technique comprises a compare of the high frequency which represents the triangular carrier signal with a low frequency signal (the sinusoidal reference waveform).

The control strategy uses the digital unipolar DPWM patterns to control the injected current in phase with the grid voltage. The control is based on using digital unipolar DPWM patterns for different modulation index ma and the phase shift angle of the inverter output voltage as control parameter. This control strategy allow the control of power injected into the grid. The output current amplitude and the power factor can be controlled, changing the power factor; the injected inductive or capacitive reactive power can be dynamically changed and controlled. Digital implementation of the control provides improvements over their analogue one. Immunity to the noise and insensitiveness in the changes of voltage and temperature. Field-Programmable Gate Array (FPGA's) implementation give suppleness in changing the designed circuit, easy and fast circuit modification without modifying the hardware and rapid prototyping

2. LITERATURE SURVEY

Gustavo C et al presents a comparative analysis of possible contributions of PV Smart-Inverter's control strategies for voltage regulation in low voltage distribution networks. A set of metrics were used to quantify the performance of each control, and the 12-bus benchmark of CIGRE was used ´ in PSCAD/EMTDC® software. Several scenarios were analyzed by an automated simulation routine that was developed to run a large number of simulations scenarios. The obtained results indicate the capability of each control strategy to improve the voltage profile for every level of PV penetration

Majumdar et al demonstrated the charge control circuitry in this paper. It can be modeled on a much larger scale and used in power distribution systems where energy is generated from solar intensity. As the demand for alternative energy resources is on its way to touch its peak in the forthcoming years, this charge regulation mechanism can surely prove a boon as a source of power. With the help of this mechanism, desired output, according to the external load connected, can be obtained from a photovoltaic module.

Kurdkandi et al presented a new DC-DC switched-capacitor converter with the potential of output voltage regulation for photovoltaic applications. The proposed topology consists of an extended high voltage gain converter along with a buck converter. The extended high voltage gain converter is operated with a fixed conversion gain whereas the buck converter is controlled to do the maximum power point tracking (MPPT) which is an important advantage of proposed structure. The most important benefits of the proposed structure are approximately continuous input current, reduction of the number of power electronic switches and costs. A comparison with other similar structures is given to show the merits of the proposed topology. The operation of proposed converter is verified using experimental results.

Wang et al proposed a switch on/off control scheme for CBs to control the voltage difference within a certain value. As long as the voltage difference can be reduced, the OLTC transformer can successfully eliminate overvoltage and low voltage problems through adjusting its tap operations. The proposed method can facilitate future PV integration with large scale into distribution systems.

Hong et al presents a novel interval type-II fuzzy logic system (IT2 FLS)-based controller, which consists of current and voltage regulators, applied to the STATCOM, to mitigate bus voltage variations caused by large disturbances (such as intermittent generation of photovoltaic arrays). The current regulator is used to produce the phase angle at the voltage-source converter in the STATCOM while the voltage regulator outputs the current reference on the quadrature axis for the STATCOM. The parameters of the upper/lower membership functions and control gains are optimized by particle swarm optimization. A realistic 10-bus distribution system is used to demonstrate the effectiveness of the proposed method. Comparative studies reveal that the proposed method outperforms traditional PI and Type-I FLS-based methods.

3. EXISTING SYSTEM

Traditional Control Scheme in the cascaded control scheme of Fig. 2, the low bandwidth of the outer PV voltage loop justifies approximating the fast inner current loop as a unity gain (Ig I ∗ g = 1). Therefore, closed loop PV voltage regulation stability is studied based on the scheme of Fig. 3, where (7) is the plant seen by the voltage controller, unstable at the left of the MPP, where rpv > Rpv.

$$G_{v_{\mathrm{pv}},\mathrm{cl}}(s) = \frac{\tilde{v}_{\mathrm{pv}}}{\tilde{v}^*_{\mathrm{pv}}} = \frac{-C_{\mathrm{v}}(s)\,G_{v_{\mathrm{pv}}I_{\mathrm{g}}}(s)}{1 - C_{\mathrm{v}}(s)\,G_{v_{\mathrm{pv}}I_{\mathrm{g}}}(s)}$$

has no RHP poles. Hence, using a proportional-integral (PI) voltage controller Cv (s) = kpv + kiv s , closed-loop stability is granted if the denominator of (8), D (s), has no RHP roots. This is:

$$D(s) = s^2 + s(\omega_{\mathrm{p}} - k_{\mathrm{pv}}K) - k_{\mathrm{iv}}K,$$

$$K = \frac{-E_{\mathrm{g}}}{2V_{\mathrm{pv}}C}, \qquad \omega_{\mathrm{p}} = \frac{1}{C}\left(\frac{1}{r_{\mathrm{pv}}} - \frac{1}{R_{\mathrm{pv}}}\right)$$

where the gain and angular frequency of the pole in equation, respectively, are given in equation. If all coefficients of s in pole equation are positive, then the roots of D (s) lie in the left half of the complex plane (LHP), and the closed-loop system (8) is stable. This condition is satisfied as long as the coefficient of s in (9) is positive, i.e., ωp − kpvK > 0, which, using below equation, translates to a constraint on the proportional gain of the PV voltage controller:

$$k_{\mathrm{pv}} > -\frac{2V_{\mathrm{pv}}}{E_{\mathrm{g}}}\left(\frac{1}{r_{\mathrm{pv}}} - \frac{1}{R_{\mathrm{pv}}}\right).$$

Since the proportional gain, kpv, is positive, constraint (11) is satisfied whenever the PV source operates in the constant voltage region (on the right of the MPP) where Rpv > rpv, and the right hand side term in (11) is negative. At the MPP, where Rpv = rpv, the system is also stable as (11) is satisfied. Conversely, when the PV source is in the constant current region (on the left of the MPP), where rpv > Rpv, the right hand side term in (11) is positive, and kpv needs to be greater than this positive value to ensure closed-loop stability. The right hand side term in (11) is positive, and highest, when rpv >> Rpv, therefore 1 rpv → 0 and 1 Rpv ≈ Isc Vpv, min, i.e., the PV source is operating in the constant current region at its minimum voltage, Vpv, min, and short-circuit current, Isc (see Fig. 4). Closed-loop stability is preserved in this worst case PV operating condition, if:

$$k_{\mathrm{pv}} > k_{\mathrm{safety}}\frac{2V_{\mathrm{pv}}I_{\mathrm{sc}}}{E_{\mathrm{g}}V_{\mathrm{pv,min}}}$$

where a factor, e.g., ksafety = 2, is introduced for safety. Condition (12) is equivalent to tuning the voltage controller so that the voltage loop cross-over frequency (or bandwidth), ωv, is at least twice the frequency of the worst-case RHP pole, this requirement translates into:

$$\omega_v > 2\max\left|\frac{1}{C}\left(\frac{1}{r_{pv}} - \frac{1}{R_{pv}}\right)\right| = 2\frac{I_{sc}}{CV_{pv,min}},$$

which considers the worst-case scenario when the PV operating point is in the constant current region at Vpv, min, Isc. The loop-gain [29, p. 241] of the PV voltage loop in Fig. 3 is:

$$T_v(s) = C_v(s)\,G_{v_{pv}I_g}(s).$$

At the cross-over frequency, ωv, |Tv (jωv) | = 1 and being ωv far removed from the pole frequency of (7), then |Tv (jωv) | ≈ kpvEg 2VpvCωv, yielding in ωv = kpvEg 2VpvC, which substituted in (13) results in the constraint for kpv to avoid closed-loop instability:

$$k_{pv} > \frac{4V_{pv}C\omega_{RHP}}{E_g}, \qquad \omega_{RHP} = \frac{I_{sc}}{CV_{pv,min}}.$$

where rap is the worst-case RHP frequency of the pole in (7). Condition (15) for kpv, derived around the bandwidth of the PV voltage loop, is therefore identical to condition (12), determined by studying the stability of the closed-loop system (8). Finally, the voltage controller integral gain, kiv, is chosen to ensure that there is no phase delay caused by the integrator at ωv, thus posing the PI zero, located at kiv kpv, no less than one decade far from ωv, yielding

$$k_{iv} \le 0.1k_{pv}\omega_v.$$

In summary, closed-loop stability of the traditional PV voltage regulation scheme (Fig. 2 and Fig. 3) is undesirably dependent on the value of PI controller proportional gain, kpv. In the constant current region of the PV source, an insufficient value of kpv, would result in the violation of above equation, with detrimental effects on the PV voltage regulation.

4. PROPOSED SYSTEM

This work analyses the PV voltage regulation in the single-stage single-phase PV inverter. In contrast to previous work, the PV source influence on the input voltage dynamic is analytically formalized, exposing a potential instability when the PV source is operating in its constant current region. A traditional proportional-integral PV voltage controller fails to ensure a consistent and stable voltage regulation. On the other hand, this issue is resolved by the proposed feedback linearization-based controller.

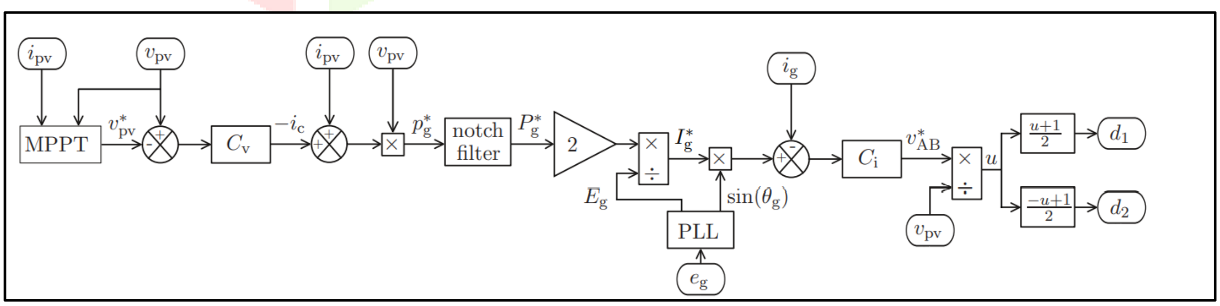

FIG. 1. PROPOSED CASCADED CONTROL SCHEME FOR PV VOLTAGE AND GRID CURRENT

Proposed Control Based on Feedback Linearization The proposed control scheme is portrayed in Fig. As before, design of the proposed PV voltage controller assumes the inner current loop to be much faster than the outer voltage loop. In other words, the measured grid current, ig, equals its reference, i ∗ g, at all times, noting that i ∗ g = I ∗ g sin (θg), and the closed-loop dynamic of the current loop does not affect the voltage loop dynamic. Therefore, the current controller remains the same as in the traditional control scheme. The scope of the outer voltage loop is still to provide the peak value of the grid current reference, I ∗ g, to the inner current loop. However, in the proposed PV voltage controller, I ∗ g is not the direct output of the voltage PI. The instantaneous power balance on the input capacitor is:

ppv − pg = pc

The capacitor current, ic, can be expressed rewriting equation as:

$$i_{\mathrm{pv}} - \frac{p_{\mathrm{g}}}{v_{\mathrm{pv}}} = i_{\mathrm{c}}.$$

Choosing the capacitor current ic = Cv˙pv as the new outer loop control input, this is the output of a linear controller, Cv (s), simply designed around the plant, so that

$$i_{\mathrm{c}} = C_{\mathrm{v}}\left(s\right)\left(v_{\mathrm{pv}}^{*} - v_{\mathrm{pv}}\right).$$

The new control variable, ic, allows to design a PI controller Cv (s) regulating the PV voltage, however the actual control input to the inner current loop, I ∗ g , must still be derived. Pursuing this objective, the instantaneous power injected into the grid is

$$p_{\mathrm{g}} = v_{\mathrm{pv}}\left(i_{\mathrm{pv}} - i_{\mathrm{c}}\right),$$

where ic is from equation. The dc component, Pg, can be extracted from equation by eliminating the double line frequency ripple component. Therefore, the term on the right-hand side of equation is passed through a notch filter, tuned to eliminate the double line frequency. Hence, the peak grid current reference, I ∗ g, is calculated from the average ac power, P ∗ g, available at the output of the notch filter. Finally, using the dc term of (3), and reminding that for the voltage loop I ∗ g = Ig, the ac peak current reference for the inner loop is:

$$I_{\mathrm{g}}^{*} = \frac{2P_{\mathrm{g}}^{*}}{E_{\mathrm{g}}}.$$

In the proposed control scheme of Fig. 5, the peak grid current reference, I ∗ g, is calculated using the output of the PI controller, Cv (s), as well as feed-forward signals from the PV source, vpv and ipv, and the output of a notch filter, P ∗ g. The feed-forward signals remove the dependence of the PV voltage regulation on the operating point of the PV source, eliminating the stability issues appearing with the traditional control when the PV source operates in the CCR (Fig. 4). Particularly, the proposed control scheme is closed loop stable, independently from the value of the PI voltage controller gains. This approach is based on the manipulation of large-signal nonlinear equations, rather than on small-signal transfer functions. Hence, proof of closed-loop stability is given directly in the time domain. Assuming that the average ac power is unaffected by the unitary-gain notch filter, the proposed control law for I ∗ g is:

$$I_g^* = \frac{2}{E_g} v_{pv} \left[i_{pv} + k_{pv} \left(v_{pv} - v_{pv}^* \right) + k_{iv} \xi_v \right]$$

$$\dot{\xi}_v = v_{pv} - v_{pv}^*$$

and substituted into the large-signal nonlinear equation (4) describing the PV voltage dynamic, gives:

$$v_{pv} i_{pv} - v_{pv} \left[i_{pv} + k_{pv} \left(v_{pv} - v_{pv}^* \right) + k_{iv} \xi_v \right] = v_{pv} C \dot{v_{pv}}.$$

Noting from equation that vpv˙ = ¨ξv (as v ∗ pv is considered constant), after some algebra, equation yields the linear differential equation:

$$-k_{pv} \dot{\xi_v} - k_{iv} \xi_v = C \ddot{\xi_v}.$$

The characteristic equation associated with (24) is

$$\frac{k_{iv}}{C} + \frac{k_{pv}}{C} r + r^2 = 0$$

In conclusion, the proposed nonlinear control law equation for I ∗ g has the benefit of linearizing the large-signal PV voltage dynamic equation, while canceling the nonlinearity of the PV generator. This scheme is closed-loop stable, regardless of the PV generator operating point, and independently of the voltage controller gains

5. RESULT & DISCUSSION

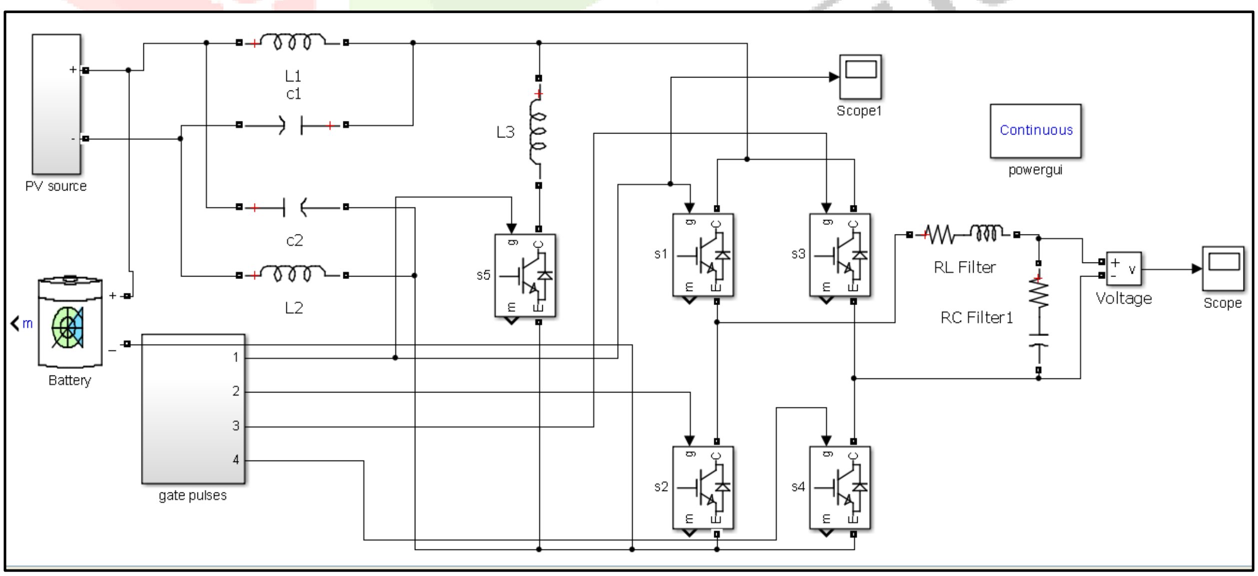

FIG:2 OVERALL MODEL

The above figure shows the Simulink model of proposed PV voltage regulation. The experiments were done for a solar input voltage with resistive load. The tests were carried out for different load conditions.

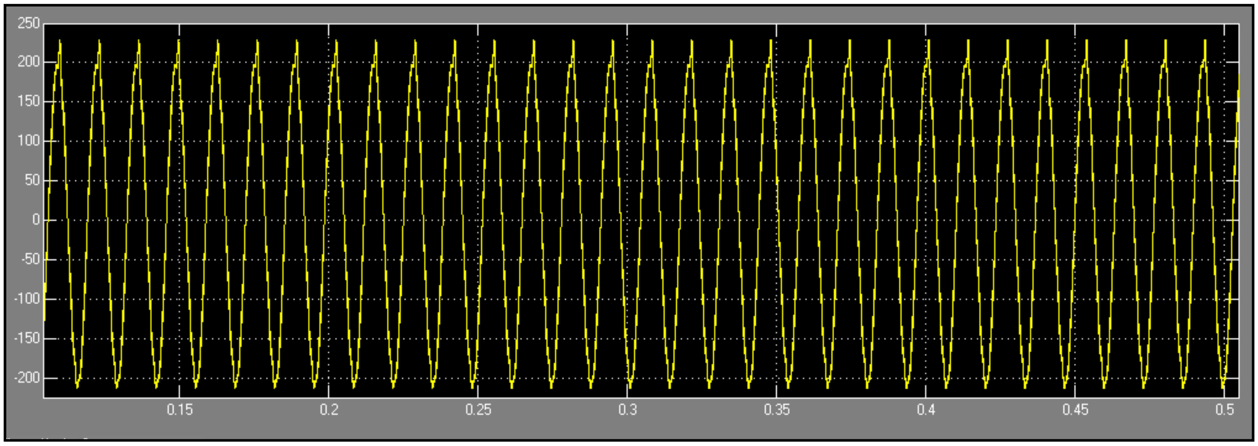

FIG:3 OUTPUT VOLTAGE OF INVERTER

The above figure shows the AC voltage of proposed inverter with feedback linearization. The ripple in the AC output voltage will be minimized by placing a capacitor at the output side. Output capacitor value can be calculated using equation based on the output voltage ripple specification

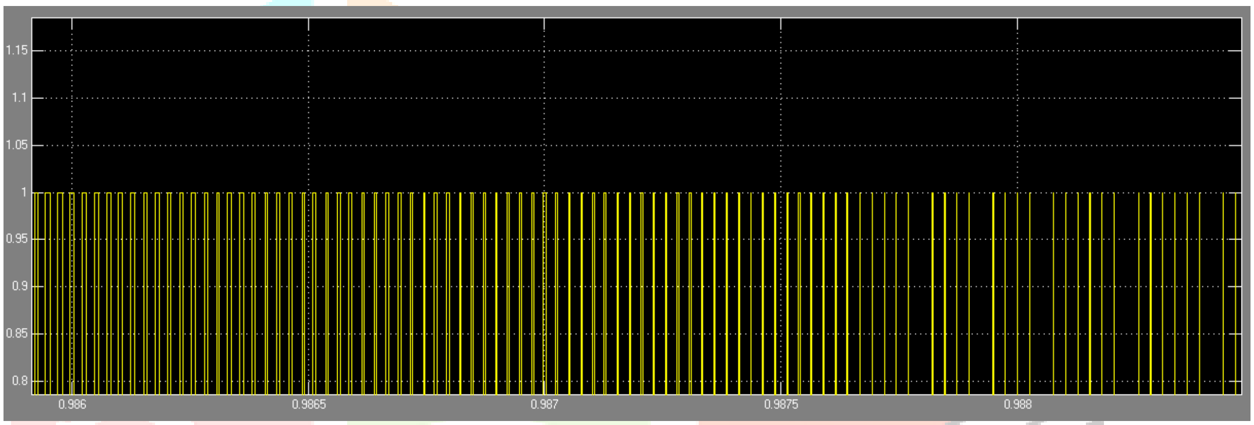

FIG:4 SWITCHING PULSE

The above figure shows the PWM generation. The positive pules switch ON the MOSFET switch and zero pulse turn OFF the MOSFET switch

5.1 HARDWARE IMPLEMENTATION RESULTS

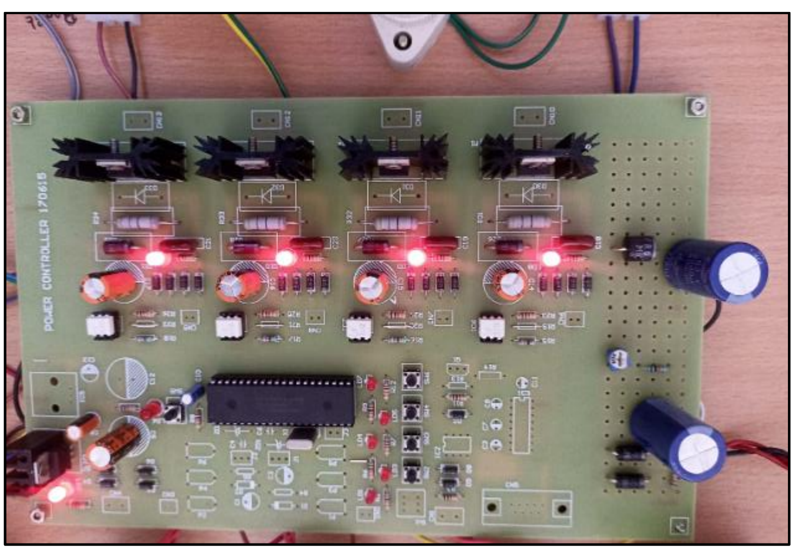

FIG: 5 IMPLEMENTATION RESULTS -CONVERTER

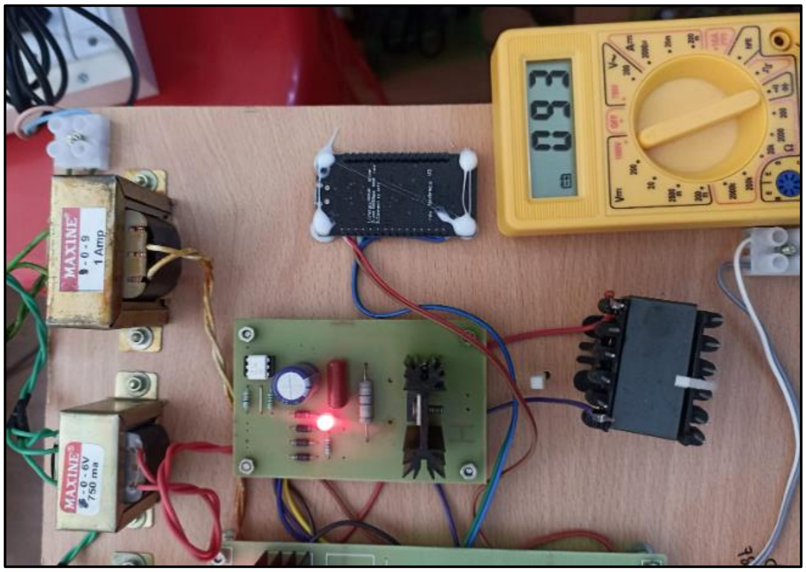

FIG :6 BOOST CONVERTER

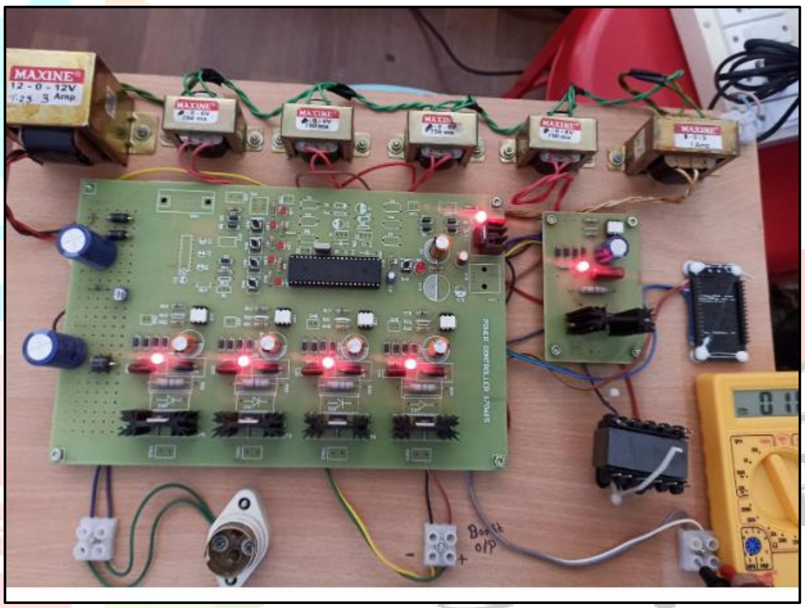

FIG :7 INPUT VOLTAGE

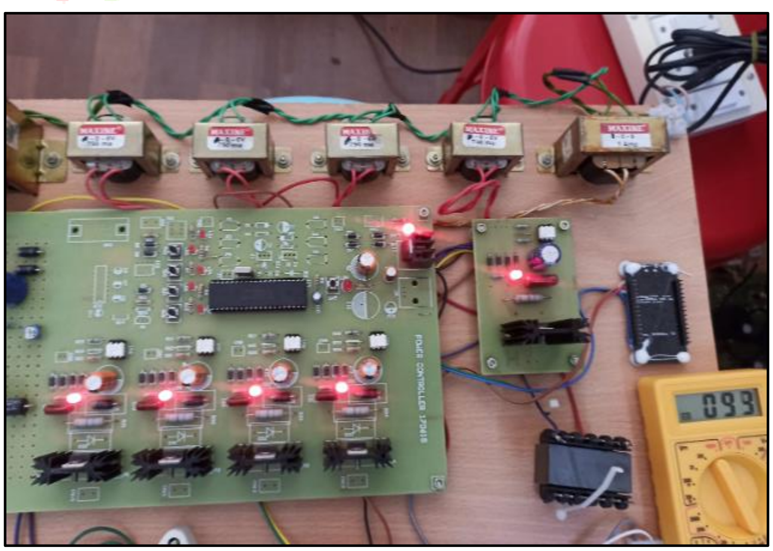

FIG: 8 OUTPUT VOLTAGE

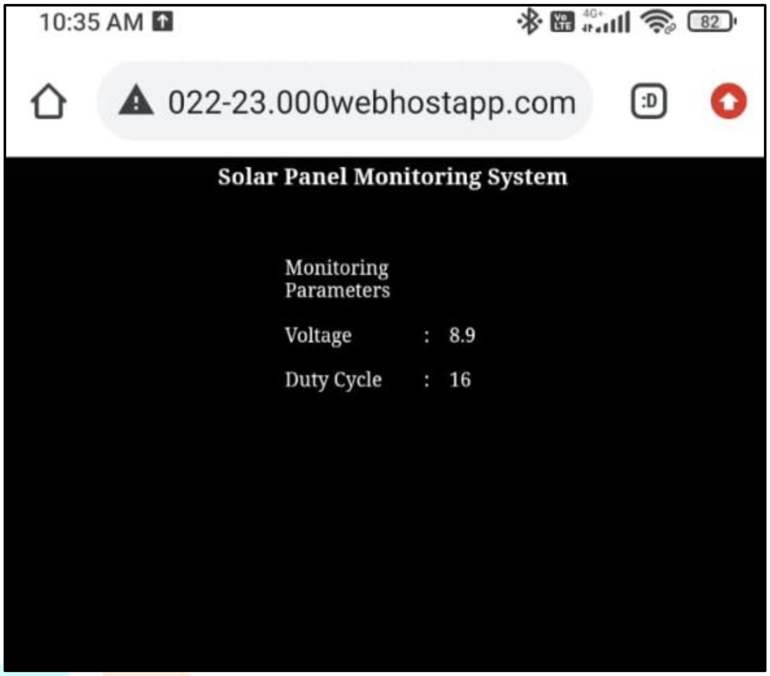

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FIG :9 SERVER MONITORING

6. CONCLUSION

This project analyzed the input voltage regulation in the single-stage single-phase PV inverter, taking into account the dynamic model of the PV source. An unstable pole in the plant transfer function describing the PV voltage behavior was demonstrated to have detrimental effects on PV voltage regulation and closed-loop stability, when adopting a traditional linear PV voltage control scheme. In contrast, the proposed PV voltage controller based on feedback linearization resolved these issues. The combination of feed-forward measurements of PV voltage and current to the output of the PI voltage controller, removed the dependence of the PV voltage regulation from the operating point of the PV source, eliminating the closed-loop instability. In summary, this research produced two main contributions. Firstly, it significantly advanced existing modeling knowledge of single-stage single-phase PV inverters. Secondly, it produced a new PV voltage control technique, dramatically improving the PV voltage regulation especially on the left side of the MPP. While this research has unveiled an issue and proposed a solution for it, future work will aim to benchmark the proposed controller against more advanced PV voltage controllers found in the literature, whose behavior in the CCR has not yet been studied.

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