# DESIGN OF LYAPUNOV FUNCTION BASED CURRENT CONTROLLER TO CONTROL POWER FLOW FROM RENEWABLE ENERGY SOURCE TO MICROGRID SYSTEM

**Mr. Imran Altaf Patel[1], Prof. T. N.Date[2]**

*[1]PG Student, [2]Associate Professor*

*Department of EE, K. K. Wagh Institute of Engineering Education &Research, Nashik, (India)*

## ABSTRACT

*A novel current control technique, implemented in the a–b–c frame, for a three-phase inverter is proposed to control the active and reactive power flow from the renewable energy source to a three-phase generalized microgrid system. The proposed control system not only controls the grid power flow but also reduces the grid current total harmonic distortion in the presence of typical nonlinear loads. The control system shapes the grid current taking into account the grid voltage unbalance, harmonics as well as unbalance in line side inductors. The stability of the control system is ensured by the direct method of Lyapunov. A SRC is also proposed to improve the performance of the current controller by estimating the periodic disturbances of the system. The proposed control system provides superior performance over the conventional multiple proportional-integral and proportional-resonant control methods due to the absence of the PARK's transformation blocks as well as phase lock loop requirement in the control structure. A new inverter modeling technique is also presented to take care of unbalances both in grid voltages and line side inductors.The increased penetration of nonlinear loads and power-electronics-based distributed generation (DG) systems may introduce power quality issues to the distribution power system. However, if controlled and regulated properly, the DG grid interfacing converters are able to improve the distribution system efficiency and power quality.*

***Keywords- Circulating Current, Distributed Generation (DG), Generalized Three-Phasemicrogrid Bus, Harmonic Compensation, Lyapunov Function-Based Current Controller, Nonlinear Load, Power Quality, Renewable Energy, Unbalance In Line Side Inductance.***

## I. INTRODUCTION

Microgrid is generally classified as a cluster of micro-generators either connected tothe mains utility grid or operated autonomously, usually through some voltage-source-inverter(VSI)-based interface. The modern trend is to replacemost of the micro-generators wherever possible to harness electrical power from renewable energy sources to reduce the consumption of fossil fuels. Electrical power systems are getting more and more stressed due to the increase in the power demand, limitation on power delivery capability of thegrid, complications in building new transmission-distribution infrastructures and finally all these lead to blackouts. Development of power electronic converters (PECs) along with its high-performance controllers make it possible to integratedifferent types of renewable energy sources to the microgrid. Different converter topologies as well as control methods are surveyed in detail in to integrate renewable energy sources, i.e., wind power and solar power, etc., in the power grid. In the cited papers, it can be seen that extensive research is undertaken to connect renewable energy sources to three-phase grids using three-phase pulse-width-modulated (PWM) inverters. Three-phase unbalanced grid interfaces of the microgridsystems are well documented in. A hybrid series-parallel compensator is proposed to minimize the current harmonics generation effect in a typical unbalanced three-phase microgrid system.

Grid-connected three-phase inverters are well documentedin the literature to facilitate renewable energy usage globally. The most popular topology is current controller VSI (CCVSI) mode to control the active and reactive power flow of the grid as reported in. A detailed literature survey on the power control methodologies to take care of different power quality issues related to unbalance grid interfaced through three-phase renewable energy source-based microgridinverter is reported in. It is also discussed in that high bandwidth grid active and reactive power flow control and unbalanced grid current shaping are facilitated by directly controlling the currents of the CCVSI system. The proposed work is directed toward the proposition of a high-performance current controller for such type of three-phase unbalance grid-connected inverters. High bandwidth current control for three- phase grid-connected CCVSI is reported in and in.The controllers are implemented in synchronously rotating reference frame using proportional-integral (PI) controller orstationary reference frame using proportional-resonant (PR) controller or in a–b–c frame using hysteresis controller or dead- beat controller. A predictive controller-based current control scheme implemented in synchronously rotating reference frame is proposed. It is well known that current controllers implemented in synchronously rotating reference frame suffer form the problem of grid frequency drift and hysteresis typecontrollers face the problem of finite sampling frequency if implemented in digital controllers or suffer from the problem of high power semiconductor device switching loss in the inverter if implemented using analog controller. Predictive controlleris also proposed in for balanced grid-connected active filter application. In this assume that balanced grid supply voltages and balanced inverter line side impedance interactions. However, with the increasing research in the field of microgrid, unbalanced grids are the focus of research.

In these paper, dual synchronouslyrotating frame-based current control is proposed and differenthigh performance controllers are used to have high bandwidth control in the case of unbalanced grid conditions. However, methods employed in these papers deal with symmetrical unbalance (absence of zero sequence component), balanced three- phase line-side inductors connection between the inverter and grid and also no compensation provided for the unbalanced nonlinear current drawn by the loads connected to the grid. In addition to these, implementation of such controllers needs feedback variables in both +ve and -ve rotating synchronous reference frames. Which in turn necessitates the dual frame Park’s transformation process using the software phase lock loop (SPLL). This necessitates significant online com- putation and delay due to dynamics associated with the SPLL block under sudden changes in grid phase in case of intermittent fault inside the microgrid.

In this paper, a generalized model of the three-phase CCVSIin the a–b–c frame is presented which considers unbalanced line-side inductors interfacing of the CCVSI with the grid.The grid can also have asymmetrical unbalance (presence of zero sequence voltage) condition. A Lyapunov function-based controller is proposed to facilitate the current control of such inverters directly in the a–b–c frame. Previously, a Lyapunovfunction-based current controller for the single phase grid- connected renewable energy source-based microgrid inverter is proposed . The number of controllers needed forsuch unbalanced control is shown to be only two unlikemultiple controllers as mentioned in. The proposed controller is also implemented in the a–b–c frame which eliminates the need for dual frame Park transformation as well as SPLL in the control structure. The proposed control strategy is also invariant to the fundamental frequency of the grid. The proposed control method uses the current references calculated directly in the a–b–c frame by the method as described and the successful current tracking by the CCVSI ensures propergrid active and reactive power flow along with minimum dc link voltage ripple and pure sinusoidal grid currents in the presence of nonlinear load connected at the point of common coupling (PCC) in the grid. This also eliminates the need for additional power factor correction circuit, which is commonly referred to as shunt compensator in the literature. A spatial repetitive controller (SRC) is used to estimate the predictable and unpredictable periodic disturbances to improve the performance of the Lyapunov function-basedcontroller. The proposed approach has been reported inwhere it is proposed to use high controller gains (which introduces jittering in the current tracking) and the grid voltage disturbances are sensed using additional voltage sensors and included in the control signals. However, in this paper, the method is modified to a large extent while estimating the grid voltage disturbances and other periodic disturbances by the application of SRC and eliminating the need for voltage sensors. The improved method therefore eliminates the delays as well as noise contamination of the voltage sensors and ensures acceptable values of the controller gains. Also, more detailed experimental results are provided in the present paper. The proposed approach can be applied to both six semiconductor switch-based (b–6) and four semiconductor switch-based (b–4) three-phase power converter topology, but this paper emphasizes the application of the proposed methodology on the b–6 topology. A detailed analysis of the proposed controller is provided, and adequate experimental results are also included to show the efficacy of the proposed control structure.

## II. GENERAL DISCRIPTION OF THE RENEWABLE ENERGY SOURSE BASED-INVERTER: INTERFACE BETWEEN MICROGRID AND UTILITY GRID

### 2.1 Descriptionofinverter Intraction with Microgrid

Fig..1 shows the schematic of a typical three-phase multi-bus microgridsystem connected to the utility grid at the PCC. Different distributed generators interface to the microgridand the load using PECs. The focus of this report is on the three- phase inverter interfacing the renewable energy sources to the Local Bus of the microgrid in the presence of local loads as highlighted in Fig.1.It can also be noticed that the targeted renewable energy source-based inverter is connected at the three-phase local bus directly using a set of line side inductors (choke coil). At thesame local bus, a three-phase nonlinear load is also connected. The nonlinear load draws non-sinusoidal current from the local bus.The PEC extracts power from the renewable energy sources (may be solar, wind, or fuel cell- based energy harvester) at maximum power point operation. The output of the PEC is connected to an energy storage device such as battery, which is connected to the inverter dc link.The VSI operates in CCVSI mode to have flexible power flow control through the inverter,

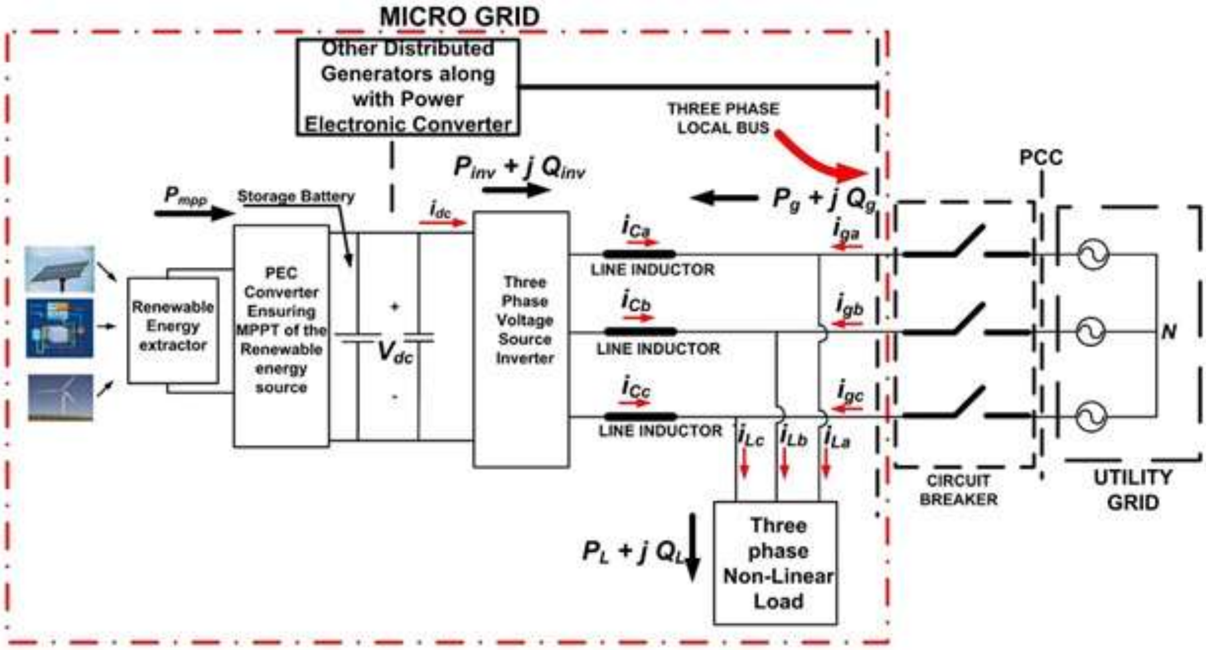


**Fig.1Typicalconfiguration of a Renewable Energy Fed Three-Phase Microgrid**

### 2.2 Control Methodology of the Inverter Current

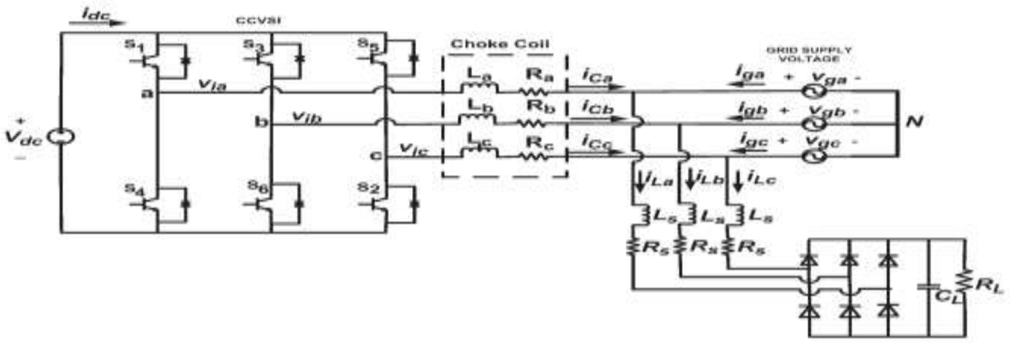


**Fig.2simplified Power Circuit of the Three-Phase Grid-Connected Renewable Energy Inverter**

In this paper, the three-phase local bus voltage is referred to as grid voltage vga, vgb, and vgc with respect to the utility grid neutral N as shown in Fig. 2. It can be understood from Fig. 5.1 that the PEC converter extracts maximum power Pmpp from the renewable energy source. The load draws average active power PL and average reactive power QL from the grid (i.e., complex load power, SL = PL + jQL). The total load active power is shared by the grid average active power Pg and the average active power provided by the inverter Pinv. The inverter active power flow is controlled in such a way that when the dc link battery is not fully charged, certain amount of activepowerPbat = Pmpp − Pinv is pumped in to the battery, and when the battery is fully charged, the full harvested power Pmppis pumped out by the inverter to be utilized by the load and the grid. Thus, it can be understood that based on the amount of the harvested renewable energy, there can be savings on the power consumption from the grid by the load. The CCVSI is controlled in such a way that the three-phase inverter currents (iCa, iCb, and iCc) follow their corresponding references to ensure a specific grid power consumption along with maintaining the grid currents (iga, igb, and igc)to be sinusoidal and drawing zero average reactive power fromthe grid. The CCVSI current references are calculated usingp–q theory-based approach to ensure minimum low-frequency dc link voltage ripple to reduce the size of the electrolytic capacitor at the inverter dc link. The details of different current reference estimation methods are analyzed in details in litrature. This report focuses on the current control methodology of the CCVSI.

## III. STATE-SPACE MODELING OF THE THREE-PHASE UNBALANCED GRID-CONNECTED INVERTER IN A-B-C

The basic grid-connected three-phase inverter topology is shown in Fig. 1. The dc voltage source vdc is assumed to be formed by the renewable energy sources as explained earlier in Fig. 2. Considering the interconnection between the generalized grid and the inverter (Fig. 2) and the isolation of grid neutral N with line side inductances are characterized with inductance and resistance, (La,Ra), (Lb,Rb), and (Lc,Rc), the state- space equations for this system (states are: x1 = iCa and x2 = iCb) can be expressed as

$$\frac{dx_1}{dt} = a_{11}x_1 + a_{12}x_2 + u_1 + d_1$$
$$\frac{dx_2}{dt} = a_{21}x_1 + a_{22}x_2 + u_2 + d_2 \qquad (1)$$

With input signal

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} v_{iac} \\ v_{ibc} \end{bmatrix}$$
$$\Rightarrow \begin{bmatrix} v_{iac} \\ v_{ibc} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}^{-1} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \qquad (2)$$

where, vimn and vgmn are the respective inverter and grid line voltages between phases m and n, respectively, with m, n ∈
a, b, c. Other coefficients are:
a11 =−((RaLb+RcLb+RaLc)/ (LaLb+LbLc+LcLa)), a12 =−((RcLb−RbLc)/(LaLb +LbLc + LcLa),
a22 =−((RbLa + RcLa + RbLc)/(LaLb + LbLc + LcLa)),
a21 =(RcLa − RaLc)/(LaLb + LbLc +LcLa),
b11 =(Lb + Lc)/(LaLb + LbLc + LcLa),
b12 =−(Lc/(LaLb+LbLc+LcLa)),
b21 =−(Lc/(LaLb+LbLc+LcLa)),
b22 =(La + Lc)/(LaLb + LbLc + LcLa),
d1 =−(((Lb + Lc)vgac − Lcvgbc)/(LaLb + LbLc + LcLa),
d2=−((−Lcvgac+(L + Lc)vgbc)/(LaLb+LbLc+LcLa).
It should be added that d1 and d2 can be regarded as thedisturbance inputs to the state equations shown in (1). In practical cases, the disturbance terms d1 and d2 in (1) consist of not only grid voltage disturbances but also unpredictable nonlinear periodic disturbances such as voltage drops due to inverter blanking time, etc., as explained in details.

## IV.DESIGN OF NONLINEAR CONTROL LAW BASED ONLYAPUNOV FUNCTION

### 4.1 Determining the Lyapunov Function-Based Control Law Toensure Current Control

It can be seen from (1) that the three-phase grid-connectedinverter consists of two states, x1 and x2. Thus, for arbitrarywaveform tracking in these two states, a nonlinear control law is derived based on the Lyapunov function method [41], i.e.,thfirst principle of absolute stability. Considering the positive definite Lyapunov function as

$$V = \frac{1}{2} e^T e \tag{3}$$

where error array e is represented as

$$e = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} x_1^* - x_1 \\ x_2^* - x_2 \end{bmatrix} \tag{4}$$

where x∗1 and x∗2 are the tracking references of x1 and x2,respectively.From Lyapunov function method of finding the stability, thefirst derivative should be a negative definite function as

$$\frac{dV}{dt} = -e^T \Gamma e \tag{5}$$

Performing derivative of (3) while using (1) and (5), the ontrol variables can be solved as

$$\begin{aligned} u_1 &= \frac{dx_1^*}{dt} - a_{11}x_1 - a_{12}x_2 + \lambda_1 e_1 - d_1 \\ u_2 &= \frac{dx_2^*}{dt} - a_{21}x_1 - a_{22}x_2 + \lambda_2 e_2 - d_2. \end{aligned} \tag{6}$$

Thus, u1 and u2 as obtained in (6) are used as control signals for controlling the line currents of the CCVSI.

### 4.2 Estimation of the Disturbance Terms d1 and d2 to Facilitate Successful Current Tracking

As explained in details in [17] that, using voltage sensors,it is impossible to accurately estimate the disturbance termsd1 and d2 because of the associated in the voltage sensors(specifically in the presence of harmonics in grid voltages) and also theunpredictable nature of the disturbances due to different nonlinear phenomena in the inverter. If the estimates of the disturbance terms d2 are different from its actual values,the control signals are affected accordingly. Using impropervalues of disturbance terms, the control laws in (6) are modifiedand used in (5) [using (1) and (4)] as

$$\frac{dV}{dt} = -e^T \Gamma e + e^T \begin{bmatrix} (\widehat{d}_1 - d_1) \\ (\widehat{d}_2 - d_2) \end{bmatrix}. \tag{7}$$

$$\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} e_{1b} \\ e_{2b} \end{bmatrix} = \begin{bmatrix} \frac{\widehat{d}_1 - d_1}{\lambda_1} \\ \frac{\widehat{d}_2 - d_2}{\lambda_2} \end{bmatrix}. \tag{8}$$

Hence, to ensure perfect current tracking, the two disturbance terms are estimated by the SRC based on the residual current errors as also reported in [17]. Following this analysis, the control laws in (6) are modified as

$$\begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} = \begin{bmatrix} u_{lf1}(t) + u_{\text{src}1}(t) \\ u_{lf2}(t) + u_{\text{src}2}(t) \end{bmatrix} \tag{9}$$

where, Lyapunov function-based control laws are represented as

$$\begin{bmatrix} u_{lf1}(t) \\ u_{lf2}(t) \end{bmatrix} = \begin{bmatrix} \frac{dx_1^*}{dt} - a_{11}x_1 - a_{12}x_2 + \lambda_1 e_1 \\ \frac{dx_2^*}{dt} - a_{21}x_1 - a_{22}x_2 + \lambda_2 e_2 \end{bmatrix}. \quad (10)$$

$$\begin{bmatrix} u_{src1}(t) \\ u_{src2}(t) \end{bmatrix} = \begin{bmatrix} -d_1 \\ -d_2 \end{bmatrix} \quad (11)$$

For a typical microgrid application, the grid voltage as well as inverter unpredictable nonlinearities do not change frequently,so the slow dynamics of SRC control laws are dominated by the fast dynamics of Lyapunov function control laws in the case of sudden change in current references. The details of the overall control system are shown in Fig. 3.

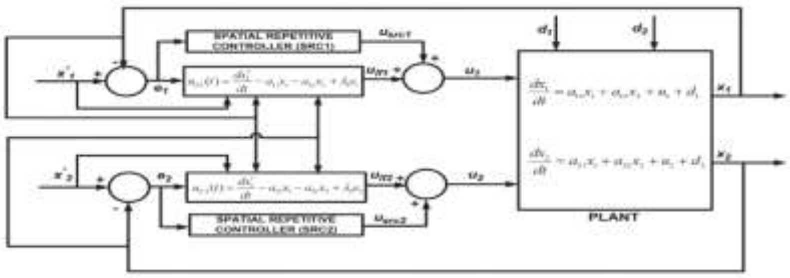


**Fig.3.Schematics of Overall Control System**

### 4.3 Ensuring the Stability of the Plugged-In Spatialrepetitive Controller in Parallel with the Lyapunovfunction-Based Controller

The stability of the overall system can be judged, by substituting (9) in (1) and the resulting state equations are as follows

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \frac{dx_1^*}{dt} + \lambda_1 (x_1^* - x_1) + d_1 + u_{src1} \\ \frac{dx_2^*}{dt} + \lambda_2 (x_2^* - x_2) + d_2 + u_{src2} \end{bmatrix} \quad (12)$$

Equation (12) can be re-arranged as

$$\begin{bmatrix} \dot{x}_1 + \lambda_1 x_1 \\ \dot{x}_2 + \lambda_2 x_2 \end{bmatrix} = \begin{bmatrix} \frac{dx_1^*}{dt} + \lambda_1 x_1^* + d_1 + u_{src1} \\ \frac{dx_2^*}{dt} + \lambda_2 x_2^* + d_2 + u_{src2} \end{bmatrix} = \begin{bmatrix} d_{mod1} + u_{src1} \\ d_{mod2} + u_{src2} \end{bmatrix} \quad (13)$$

### 4.4 Effect of Parameter Uncertainty on the Error Convergence

If (6) is observed carefully, it is seen that the parameters of the control laws, a11, a12, a21, and a22 are dependent on the actual values of the resistances and inductances of the line side inductors in the system. However, the resistances and inductances of the line side inductors cannot be estimated accurately. If the estimated values (different from the

actual values) of the system parameters are mentioned as:

$$u_1 = \frac{dx_1^*}{dt} - \widehat{a}_{11}x_1 - \widehat{a}_{12}x_2 + \lambda_1 e_1 - d_1$$

$$u_2 = \frac{dx_2^*}{dt} - \widehat{a}_{21}x_1 - \widehat{a}_{22}x_2 + \lambda_2 e_2 - d_2. \quad (14)$$

$$\frac{dV}{dt} = -e^T \Gamma e + e^T \begin{bmatrix} [(\widehat{a}_{11} - a_{11})x_1 + (\widehat{a}_{12} - a_{12})x_2] \\ [(\widehat{a}_{21} - a_{21})x_1 + (\widehat{a}_{22} - a_{22})x_2] \end{bmatrix} \quad (15)$$

$$\Rightarrow \frac{dV}{dt} = (-\lambda_1 e_1^2 + e_1 D_1(.)) + (-\lambda_2 e_2^2 + e_2 D_2(.)) \quad (16)$$

The conclusion can be drawn from (16) that, to make dV/dtnegative definite, the condition can be expressed as

$$\left|\lambda_1 e_1^2\right| > \left|e_1 D_1(.)\right|$$
$$\left|\lambda_2 e_2^2\right| > \left|e_2 D_2(.)\right|. \quad (17)$$

This can be achieved if the parameters λ1 and λ2 are
selected as:

$$\lambda_1 > \frac{\left|D_1(.)\right|_{\max}}{e_b}$$
$$\lambda_2 > \frac{\left|D_2(.)\right|_{\max}}{e_b}. \quad (18)$$

Both the errors e1 and e2 converge to the error bound eb, which is selected to be sufficiently close to 0. Satisfying (18) ensures the robustness of the proposed Lyapunov function-based controller to the parameter uncertainty of the overall system.

## V. CONCLUSION

A new current control strategy for a parallel connected three phase renewable energy source-based inverter to connect to the generalizedmicrogrid system is proposed. The control strategy is implemented directly in the a–b–c frame and is able to take care of unbalance conditions in both the grid voltage as well as line side inductances andload. The proposed method also reduces the THD of the grid current along with the proper grid active as well as reactive power control. The proposed control method is implemented in the digital controller and requiresno Park's transformation block unlike the conventional method where multiple controllers are implemented in synchronously rotating dual reference frame and gives superior performance.

Thus, the proposed method works without the necessity of the PLL. The proposed controller is also capable of rejecting the effect of grid voltage harmonics in the grid currents. The proposed controller is also shown to be independent of grid frequency. The stability of the proposed control system is described with the help of Lyapunov's first principle hence the name of the controller. A modeling method of the three- phase grid-connected inverter under unbalanced connection condition is also presented to facilitate the proposed control action. The proposed control strategy is applied on conventional six-switch topology (b–6 configuration) of three-phase inverter, and presented Mathematical modeling show the effectiveness of the controller.

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