Voltage Imbalance and Harmonics Compensation for an Autonomous Mode Microgrid using Power Droop Controller

B. Mothi Ram, P.Raja Padma Priya

Abstract: Generally, Power-Electronics-Interfaced Distributed Generation (DG) system use voltage source inverters (VSI) in a microgrid. It is the responsibility of the microgrid to support the loads when the main grid stops functioning. In off-grid mode, VSIs regulates the voltage as well as the frequency of the microgrid. As a result, the quality of the power decreases whenever imbalanced loads or electronic loads appear. This paper explores a novel strategy to mitigate both the voltage imbalance as well as harmonics in islanded mode. The control system consists of power droop regulators, internal single synchronous reference frame (SRF) in light of voltage imbalance as well as harmonic controllers which are accountable for voltage imbalance as well as harmonic mitigation and modified virtual impedance loop technique used to enhance the compensation effect further. The proposed system consists of regular Proportional-Integral (PI) regulator, Proportional-Integral cum multi-resonant (PIR) regulator as well as Proportional-Integral cum multi-resonant regulator with modified virtual impedance loop technique. The MATLAB/SIMULINK software platform is used to develop the system model and outputs are shown. The incurred value of PIR regulator with modified virtual impedance loop is compared with Proportional Integral regulator and PI cum multi-resonant regulator and is proved better.

***Index Terms*: Distributed Generation (DG), Proportional Integral (PI) controller, Proportional Integral cum multi-resonant (PIR) controller, Proportional Integral cum multi-resonant controller with modified virtual impedance loop technique, Voltage Source Inverter (VSI).**

I. INTRODUCTION

The notion of the substation is a productive approach to link all types of Distributed Generators (DGs) as a profit-friendly customer [1]. A standard AC substation generally comprises of DGs, energy storage systems (ESS) and local loads. Mostly the DGs and ESS are not in AC form. So VSIs are generally used as the couplings to AC bus [2,3].The power quality of the off-grid microgrid is decreased due to imbalanced and electric loads because it shortfalls the voltage and frequency backing from the main grid[4]. Imbalanced voltages cause damage to the machine in various forms.

Active power filters (APF) are generally used for securing the power quality in main grid [4,5]. Series Active Power Filters are generally used to minimise voltage imbalances as well as harmonics by inducing negative sequence and harmonic voltage into the distribution line by coupling transformers [6]. Nonetheless, as for the microgrid situation it is not profitable to use extra Active Power Filters for every DG. Distributed Generators consists of locomotives and conversion links. The output form of locomotives is of AC form or DC form but is transformed to DC form primarily. Consequently the DC-AC VSIs are used as the linking to join the locomotives to neighborhood AC bus of utility. The principal role of the Voltage Source Inverter is the power transfer and control. Furthermore, the voltage imbalance as well as harmonic compensation capacity can be attained by decent control of the Voltage Source Inverters when the outcome is of voltage-source genre.

A few researches were done in this regard to mitigate harmonics as well as imbalances using VSIs [7-11]. In [7], a shunt inverter is used to balance the voltages while the series inverter balances line current. But the power quality of the microgrid deteriorates because it is not supported by the utility. Negative-sequence current is induced to the utility utilising spare capacity of the inverters where only imbalanced voltage is solved and the inducing current may be too large under extreme conditions [8]. The four-phase-leg compensator can mitigate all undesirable positive, negative, and zero-sequence voltage as well as current constituents found within the unbalanced main grid**.** Extra series inverter is used which is uneconomic. The compensator is not efficient during voltage sags [11].

The proposed model consists of standard Proportional Integral (PI) controller, Proportional Integral plus multi-resonant (PIR) controller and Proportional Integral plus multi-resonant controller with modified virtual impedance loop to reduce the effect of harmonics as well as voltage imbalance. Simulation validations of the suggested strategies were included in the paper.

II. CONTROL TECHNIQUE OF VSIs IN MICROGRID

A standard AC microgrid is shown in Fig. 1a.VSIs are generally used as couplings between the DGs and the local AC bus. The simplified form of VSI is shown in Fig. 1b. As shown in Fig. 1c, power droop controllers are utilized to achieve active as well as reactive power sharing capability amongst Distributed Generators without excessive speed transmission. In Fig. 1c, the reference u^*_{sdq} for the internal voltage loop is generated by

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the power droop control loop technique. The internal voltage closed-loop transfer function is given by $G_{udq}(s)$.

A. Power Droop Control

If supposed a VSI is associated with the network through the impedance $Ze^{j\theta}$, then the active power as well as reactive power induced in the grid is obtained as

$$P = \frac{U}{Z}\left(E\cos\delta - U\right) + \frac{EU}{Z}\sin\delta\sin\theta \qquad (1)$$

$$Q = \frac{U}{Z}\left(E\cos\delta - U\right)\sin\theta - \frac{EU}{Z}\sin\delta\sin\theta \qquad (2)$$

Here E represents voltage of the VSI and U, voltage of the grid, δ shows the voltage phase angle distinction between E and U, Z and θ are the amplitude and phase of the impedance, respectively. Mostly, the line impedance of the framework is inductive in nature. This implies $\theta \cong \frac{\Pi}{2}$ and $Z \cong X$.

Generally δ is devised to be very small to maintain stability of the system. So (1) and (2) can be modified into (3) and (4).

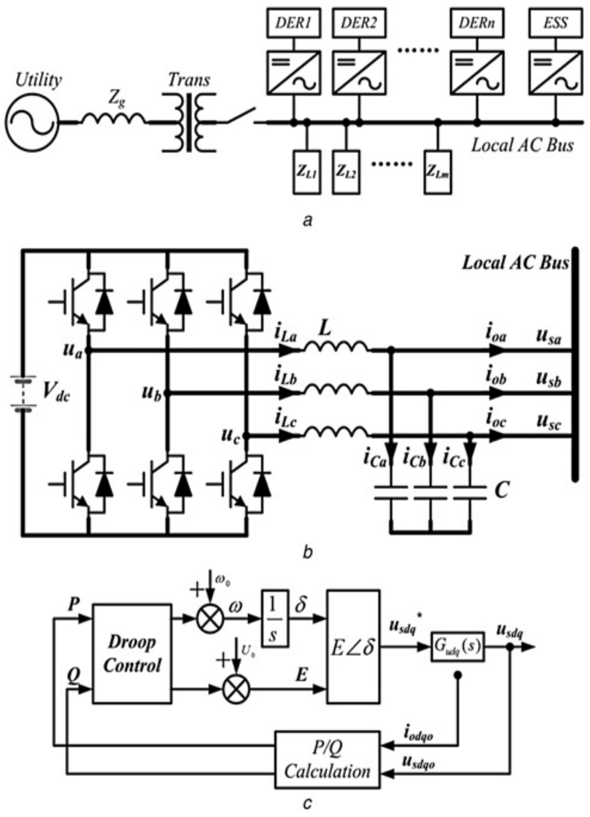

Fig 1.Simplified regulatory of Distributed Generators connected in AC microgrid
a) Standard AC microgrid with Distributed Generators and loads
b) Standard diagram of a VSI as a DG tie-up
c) Power droop control loop of DGs tie-up

$$P = \frac{EU}{X}\delta \qquad (3)$$

$$Q = \frac{U\left(E - U\right)}{X} \qquad (4)$$

From (3) and (4), it can be wrapped up that active power corresponds to the voltage phase angle variance δ and reactive power corresponds to voltage amplitude difference E-U. To regulate the power that is applied to VSI, the following strategies expressed under can be used.

$$\omega = \omega_0 - k_p \cdot \Delta P \qquad (5)$$

$$E = E_0 - k_q \cdot \Delta Q \qquad (6)$$

where ω_0 is the measured frequency, E_0 is the evaluated voltage amplitude, k_p / k_q is the active power calculated under reactive power droop coefficient and $\Delta P / \Delta Q$ is the feedback active power calculated under reactive power error between output power and power reference, respectively.

B. Internal Voltage as well as Current Control loops of the VSI

The variable vectors are only presented in stationary reference frame. To represent them in both stationary reference frame 'abc' and fundamental positive sequence (FPS) synchronous reference frame 'dq', the inner voltage and current loops are implemented as [12]. The closed loop transfer function of the current as well as voltage loop shown in [12] can be represented as follows:

$$G_i(s) = \frac{i_{Ldq}(s)}{i^*_{Ldq}(s)} = \frac{G_{iL}(s)\cdot 1/\left(sL + r_L\right)}{1 + G_{iL}(s)\cdot 1/\left(sL + r_L\right)}$$

(7)

$$u_{sdq}(s) = \frac{G_{us}(s)\cdot G_i(s)\cdot\left(1/sC\right)}{1 + G_{us}(s)\cdot G_i(s)\cdot\left(1/sC\right)}\cdot u^*_{sdq}(s) - \frac{\left(1/sC\right)}{1 + G_{us}(s)\cdot G_i(s)\cdot\left(1/sC\right)}\cdot i_{odq}(s)$$

(8)

where $G_{iL}(s) = k_{ip} + k_{ii}/s$ and $G_{us}(s) = k_{vp} + k_{vi}/s$ if PI controllers are used. The terms used are defined as follows:

u_{abc}, u_{dq}: output voltage of the 3-ϕ IGBT bridge
i_{Labc}, i_{Ldq}: filtering inductors' current
u_{sabc}, u_{sdq}: AC bus voltage
i_{oabc}, i_{odq}: output current of VSI

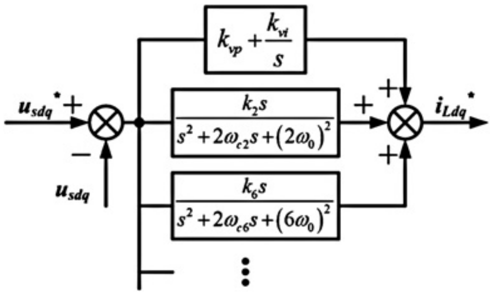

Fig 2 PI plus multi-resonant (PIR) controller/regulator

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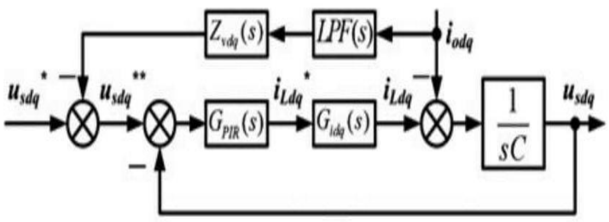

Fig 3. Suggested voltage control scheme with modified virtual output impedance loop

Assuming that Proportional-Integral regulators are utilised, the closed loop transfer functions can be written as

$$G_u(s) = \frac{G_{us}(s)\cdot G_i(s)\cdot (1/sC)}{1+G_{us}(s)\cdot G_i(s)\cdot (1/sC)} \quad (9)$$

$$Z_0(s) = \frac{(1/sC)}{1+G_{us}(s)\cdot G_i(s)\cdot (1/sC)} \quad (10)$$

C. Virtual impedance loop

By integrating an additional regulatory loop to the internal voltage loop, virtual output impedance is deduced. Since it is lossless and costless, it is the best pick for VSI-based DG interface. It is expressed as follows

$$Z_{vsq}(s) = \begin{bmatrix} sL_v + r_v & -\omega L_v \\ \omega L_v & sL_v + r_v \end{bmatrix} \quad (11)$$

The VSIs output voltage after voltage loop reference is altered by virtual impedance loop is given by (12)

$$u_{sdq}(s) = G_u(s)\cdot u_{sdq}^*(s) - \big(G_u(s)\cdot Z_{vdq}(s) + Z_{odq}(s)\big)\cdot i_{odq}(s) \quad (12)$$

Here $G_u(s)$ is closed loop transfer function and $Z_{odq}(s)$ is output impedance without virtual impedance loop. The output impedance when virtual impedance loop exists is concluded to be $Z_D(s)$ where $Z_D(s)$ is given by (13).

$$Z_D(s) = G_u(s)\cdot Z_{vdq}(s) + Z_{odq}(s) \quad (13)$$

The effective operation of the virtual output impedance is constrained by the voltage loop.

III. RECOMMENDED REGULATORY APPROACH FOR VOLTAGE IMBALANCE AS WELL AS HARMONIC MITIGATION

Three-wire AC bus is generally utilised in VSIs, induction motors, rectifiers and forth in low voltage three-phase microgrid applications. The unbalanced loads cause the unbalanced voltage of VSI which involves the fundamental positive-sequence (FPS), negative-sequence as well as zero-sequence components. Be that as it may, the zero-sequence voltage does not engender zero-sequence current in a three-phase three-wire system and hence it is not under thought. Non-linear loads, for example, diode bridge rectifier causes typical voltage harmonics which are fifth, seventh, eleventh and forth.

It is necessary to run every compensation loops under the equivalent SRF in order to cut down the closed-loop control and compensation estimate. Typical Proportional Integral controller in FPS synchronous reference frame (SRF) can maintain zero-error tracing capacity for 0Hz components only. It is thus used to handle the 'DC' component. But resonant regulators are selected for regulating the zero-error tracing capability on $2f_0$, $6f_0$ and $12f_0$ AC components. According to the above theory, the PIR controller is utilized to mitigate voltage imbalance that is shown in fig 2.

The used PIR controller is given by (14). It is further modified as in (15).

$$G_{PIR}(s) = k_{vp} + \frac{k_{vi}}{s} + \frac{k_2 s}{s^2 + 2\omega_{c^2} s + (2\omega_0)^2} + \frac{k_6 s}{s^2 + 2\omega_{c^6} s + (6\omega_0)^2} + \cdots \quad (14)$$

$$u_{sdq}(s) = G_{ur}(s)\cdot u_{sdq}^*(s) - \big(G_{ur}(s)\cdot Z_{vdq}(s) + Z_{ordq}(s)\big)\cdot i_{odq}(s) \quad (15)$$

The closed-loop voltage transfer function is indicated by (16). The output impedance without virtual impedance-loop is indicated by (17).

$$G_{ur}(s) = \frac{G_{PIR}(s)\cdot G_i(s)\cdot (1/sC)}{1+G_{PIR}(s)\cdot G_i(s)\cdot (1/sC)} \quad (16)$$

$$Z_{ordq}(s) = \frac{(1/sC)}{1+G_{PIR}(s)\cdot G_i(s)\cdot (1/sC)} \quad (17)$$

It is further written as (18)

$$Z_{Dr}(s) = G_{ur}(s)\cdot Z_{vdq}(s) + Z_{ordq}(s) \quad (18)$$

The network components and regulator parameters are provided in table 1 and table 2 respectively. The parameters are derived using the trial and error method.

IV. TRANSFORMED VIRTUAL IMPEDANCE LOOP

A low-pass filter is added in virtual impedance loop so as to diminish the harmonic voltage drop over the total output impedance. The harmonic ingredients in i_{odq} are significantly reduced as shown in the following figure. 3.

Table 3 Comparability between the output voltage imbalances as well as THDs of different control strategies

Sl no:	Type of controller	PI controller	PI plus multi-resonant controller	PI plus multi-resonant controller with modified virtual impedance loop
1.	Output voltage imbalances under specific control strategy	5	0.4	0.3
2.	THD under specific control strategy	26.87%	4.86%	3.78%

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Table 1: Values of the model

V_{dc},V	L, mH	rL, Ω	C, µF	Lv, mH	Rv, Ω	U0, V	ω0, rad/s	fs, Hz	P0, W
600	12	0.2	2.2	10	0.5	350	2Π*50	10,000	2000

Table 2: Values of the Controllers

k_p	k_q	k_{ip}	k_{ii}	k_{vp}	k_{vi}	k_2	k_6	k_{12}	ωc_2	ωc_6	ωc_{12}
$2*10^{-3}$	$5*10^{-3}$	150	0.23	0.01	10	5	10	10	0.628	1.89	3.77

The transfer function for the low-pass filter applied is given by (19).

$$LPF(s)=\frac{\omega_f}{s+\omega_f} \qquad (19)$$

The cut-off frequency of the LPF should not be too low as it degrades the dynamic response of virtual impedance technique and it must be lesser than the determined voltage harmonic frequency i.e., ω_f =2Π*10rad/s. The voltage loop after the modified virtual impedance loop included is in (20).

$$u_{sdq}(s)=G_{ur}(s)\cdot u^{*}_{sdq}(s) - \left(G_{ur}(s)\cdot Z_{vdq}(s)\cdot LPF(s)+Z_{ordq}(s)\right)\cdot i_{odq}(s) \qquad (20)$$

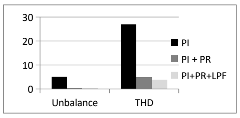
The total output impedance of the VSI when LPF is applied is given by (21).

$$Z_{Df}(s)=G_{ur}(s)\cdot Z_{vdq}(s)\cdot LPF(s)+Z_{ordq}(s) \qquad (21)$$

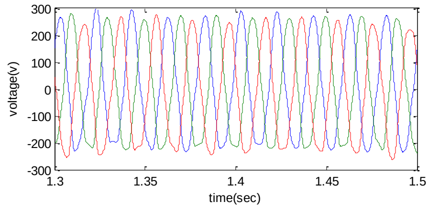
The output voltage imbalances as well as THDs of various control techniques are given in table 4.The values that are obtained in the table 3 are represented diagrammatically in the table 4 using bar graphical representation.

V. SIMULATION RESULTS

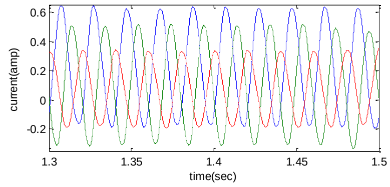
Table 4 Diagrammatic comparability among the output voltage imbalances and THDs of various control strategies



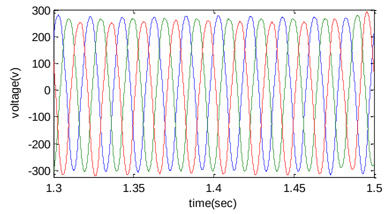
The proposed model of PI cum multi-resonant regulator virtual impedance loop is verified in MATLAB/SIMULINK software. The three scenarios included in this model are the following: (a) the PI voltage regulator (b) the PI cum multi resonant regulator (c) the suggested PI cum multi resonant regulator with modified virtual impedance loop technique. The simulation results are represented in the figure.4 in order to state the effectiveness of the proposed method.



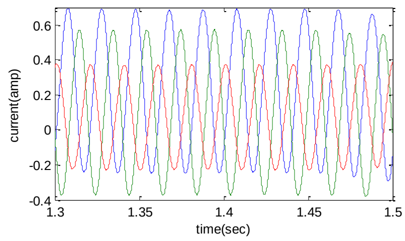
(a) Voltage waveform of the PI controller



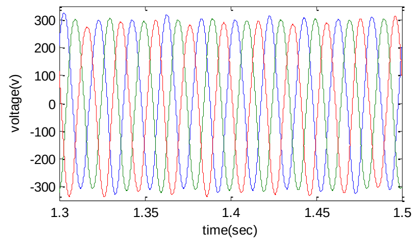
(b) Current waveform of the PI controller



(c) Voltage waveform of the PI cum multi-resonant controller



(d) Current waveform of the PI cum multi-resonant controller



(e) Voltage waveform of the recommended PI cum multi-resonant controller with modified virtual impedance loop

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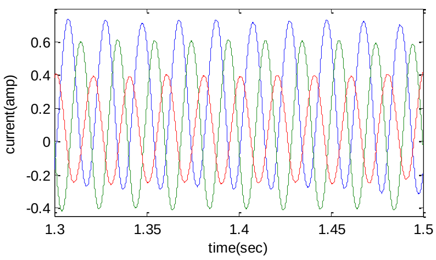

(f) Current waveforms of the recommended PI cum multi-resonant controller with modified virtual impedance loop

Fig. 4 Simulation results of the VSI in the islanded microgrid with different control strategies

The load condition of simulation is listed below:

- Step I: At 0 s, the microgrid is started with no load.
- Step II: At 1s ,3 ϕ balanced resistive load 500W is switched ON.
- Step III: At 1.2 s,1 ϕ resistive load 300W is in between AB phase.
- Step IV: At 1.3 s,3 ϕ diode bridge rectifier load 250W is ON

The parameters in table 3 are obtained from the simulation outputs of the VSI in the autonomous mode microgrid with three different control techniques. The simulation results are represented in the figure.4 to state the efficiency of the suggested technique. As seen from the figure.4, it can be observed that the performance of PI controller is not convincingly satisfactory, whilst the voltage imbalance as well as harmonic compensation is decreased to some extent by using the PIR controller method. By using the proposed method, PI cum multi-resonant regulator with modified virtual impedance loop technique the voltage imbalance as well as harmonic compensations is improved further.

VI. CONCLUSION

This article presents a FPS SRF-predicted control procedure for the voltage imbalance as well as harmonic compensation of the power electronic interfaced Voltage Source Inverters utilized in autonomous mode microgrid. The power droop loops as well as the virtual output impedance loops includes voltage recompense loops. The implemented procedure in this article includes SRF with PI regulator regulates the voltage and multi-resonant regulator compensates the voltage imbalance as well as harmonic compensation.

In this paper, the proposed control techniques are PI voltage regulator, PI cum multi-resonant voltage regulator as well as PI cum multi resonant regulator with modified virtual impedance loop. The MATLAB/Simulink outputs for above three different control techniques are shown to certify the efficiency of the recommended control strategy.

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