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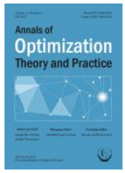

Fuzzy logic based controller for optimization of voltage unbalance compensation in an autonomous electric microgrid

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Abstract Recently, there has been an increasing utilization of distributed generators (DGs) in electric power systems not only to supply the demand power of the grid but also to enhance the power quality. In this paper, a new control scheme is proposed for optimization of voltage unbalance compensation in an autonomous microgrid. Adaptive fuzzy PI controller (AFPIC) is applied to a voltage compensation loop which modifies the droop control based inverter reference voltage. Virtual impedance loop is used to enhance the operation of droop control. Voltage unbalance factor (VUF) is calculated by positive and negative sequence components of the output voltage and compared with the maximum threshold. Second-order generalized integrator (SOGI) is used to extract the voltage positive and negative sequence. In the proposed method, microgrid has the dynamic potential of decreasing the VUF below the standard value in all kinds of load conditions while the conventional methods are designed only for a specific load operating point. Proper voltage regulation is also satisfied by back to back embedded voltage and current controllers. A sample microgrid is analyzed in presence of single phase unbalanced load and Matlab simulation results are given to show the effectiveness of the proposed controller.

Keywords Distributed generation; Fuzzy logic; Microgrid; Voltage unbalance

1. Introduction

The interconnection of small generation systems and energy storage devices to low voltage electric distribution network will lead to the microgrid concept. These power sources give the capability of decentralized generation and are known as distributed energy resources (DERs) (Chandak and Rout, (2021), Jirdehi *et al.*,(2020)). A microgrid can operate in two different modes. In interconnected mode, microgrid is connected to the main upstream grid or power network. It is supplied from or injecting power into it. Other mode is autonomous or islanding operation and the microgrid is disconnected from distribution network (Hemmati *et al.*,(2020), Bouaicha *et al.*, (2020)).

Utilization of DERs improves the service reliability. Moreover, in concept of islanding microgrid it extends up the possibility of making energy resources responsible for local power quality enhancement in a way that is not conceivable with conventional centralized power generation (HOSSAM-ELDIN *et al.*, (2019), Thomas *et al.*, (2020)).

The basic goal for DGs in a microgrid is to achieve accurate power sharing while regulating the microgrid voltage amplitude and frequency. One way is centralized control of a microgrid based on communication infrastructure (Xu *et al.*,(2020), González *et al.*,(2021), Aghanoori and Masoum (2020)). However, in remote areas with long distance between DERs, it is costly and even impractical to use communication link. Decentralized controllers eliminate communication links. Thereby power sharing for microgrid generators is investigated by means of Droop controllers and has shown desirable performance. Basic principles of droop control method are presented in (Brabandere *et al.*,(2007), Tayab *et al.*,(2017)).

Droop control is modified in many researches in the area of microgrid stability or power quality enhancement. In (Chandorkar *et al.*, (1993), Katiraei and Iravani (2006)) a static droop compensator is reported for load demand sharing. Droop control scheme is enhanced featuring the transient response performance in (Guerrero *et al.*, (2004)). To decrease the active and reactive power coupling, droop controllers with virtual frequency-voltage frame (Li and Li, (2011)) and virtual output impedance (Chiang *et al.*, (2017)) are discussed. For harmonic distorted nonlinear loads, harmonic based droop controllers are proposed in (Moussa *et al.*, (2017), Munir *et al.*, (2020), Peng *et al.*, (2019)).

One of the most important issues in microgrid operation is the presence of unbalanced loads. The main cause of voltage unbalance is unequal distribution of single phase loads. These loads cause different voltage drops in three phases of grid feeders and consequence voltage unbalance in the other load buses. Voltage imbalance has improper effect on the operation of induction motors, power electronic based devices and other sensitive loads.

In (Cheng *et al.*, (2009)) each DG operates as a conductance for the negative sequence of the main frequency. By this technic voltage imbalance is reduced. A droop characteristic is defined between negative sequence of conductance and reactive power and is known as $Q^{-} - G$ droop control. In this method the compensation signal appears as a disturbance for the voltage control loop and there is a trade-off between voltage regulation and voltage unbalance compensation.

Direct modification of the inverter reference voltage is used in (Savaghebi *et al.*, (2012)) where the voltage unbalance compensation signal is the input of voltage controller. The positive sequences of active and reactive powers are used to determine the reference frequency and voltage according to the droop characteristics. Negative sequence of the reactive power is utilized for producing the compensation reference signal.

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For unbalance compensation in the microgrid the reactive power-conductance control loop is applied for negative sequence currents regulation of the dispersed inverters (Wang *et al*., (2012)). A same approach is used in (Wang *et al*., (2008)) where a double fed induction generator is the case study and by the potential of this micro source negative sequence current is compensated.

In [24] two control structures in different synchronous frames with opposite directions are applied to control the positive and negative sequence currents. In positive sequence frame, control is based on the reverse droop characteristic. Negative sequence current-negative sequence voltage droop characteristic is applied for the negative sequence frame. By this control method the line voltage unbalance is compensated and the unbalanced load negative sequence current is shared among the generators according to their capacity. Due to having two parallel control structures for creating PWM switching pulses, this method has low reliability.

In (Rezaei and Afsharnia, (2011)) positive, negative and zero sequences are separately controlled. This study achieves proper voltage regulation, symmetrical voltages and low harmonic distortion. Negative Sequence Impedance Controller is presented in (Hamzeh *et al*., (2012)). This method reduces the negative sequence current and increases the overall microgrid efficiency. It is applied when the DG has no capacity to supply the negative sequence current. Virtual impedance is implemented in the control system and controls the unbalanced load current.

In (Savaghebi *et al*., (2012)) multilevel centralized controller is proposed. Primary level consists of power, voltage and current controllers and the virtual impedance loop. Secondary control level is designed to reduce the voltage unbalance in the point of common coupling (PCC) of microgrid. PI controller is used to reduce the difference between voltage unbalance factor and its reference value. Communication link is required between PCC and DGs to send the control signals which will decrease the system reliability.

Different attempts have been made in previous studies on voltage unbalance compensation especially in microgrids and satisfying results have been achieved. All the studies have compensated a fix predetermined unbalanced load while in a real microgrid the unbalanced loads are connected and disconnected continuously form the utility. The unbalance factor has not a fixed value and the system operating point is steadily changing. Some other methods have low reliability or low voltage regulation.

In order to have a comprehensive and dynamic control mechanism for unbalance compensation, adaptive fuzzy PI controller is applied to the voltage unbalance compensation loop in a droop controlled based microgrid. The proposed method has the capability of proper power sharing in the microgrid while satisfying the standards for the voltage unbalance in a grid. In section 2 the methodology is discussed in detail and in section 3 the controller is applied to a sample microgrid. Matlab simulation results show the performance of the proposed method.

2. Proposed methodology

Proposed control method for the DG is shown in Figure 1. Voltage unbalance compensation mechanism is combined with droop controller for power sharing and voltage and current controllers.

All the DGs of the controlled microgrid are inverter based. They are assumed to have ideal DC voltage as an input of the voltage source converter. In the other words the dynamics of the primary source is neglected. For the low inertia distributed energy resources like micro turbine and fuel cell it is necessary to have energy storage system and voltage regulating capacitor to have an ideal DC output voltage.

There is a low pass LC filter in the output of inverter, in order to eliminate the high frequency harmonics caused by the switching system. Input signals of the controllers include voltage and current measured before and after the filter. Further, detailed descriptions of the embedded controllers are discussed.

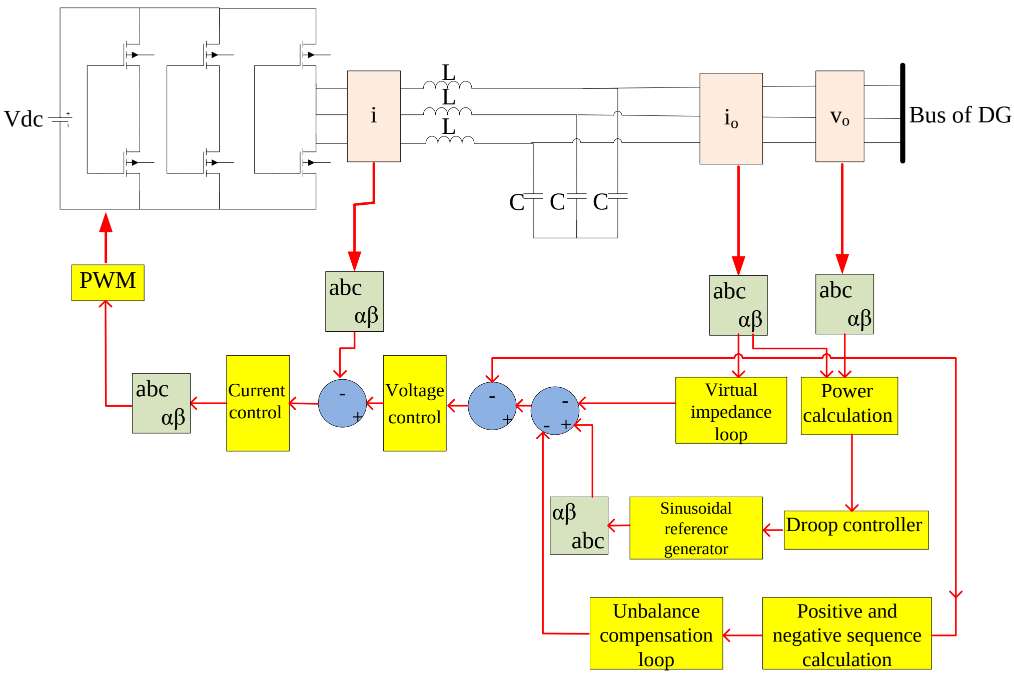

Figure 1. Proposed control system of each DG in the microgrid.

2.1. Power controller

Droop control method is the conventional way to share the demand active (P) and reactive (Q) powers among the generators in an autonomous microgrid. It mimics the operation of exciter and governor of a synchronous generator and produces the reference frequency and voltage of each DG. Considering a micro source connected to a grid with inductive impedance, the output voltage amplitude (v) depends on the generated Q while

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the frequency (ω) depends on the generated P. This concept can be represented by (1) and (2) (droop equations) (Liu *et al*., (2020)).

$$\omega = \omega_n - k_1 P \quad (1)$$

$$v = V_n - k_2 Q \quad (2)$$

According to equation (1), frequency of each generator changes any time when a variation is happened in load active power. When this variation occurs, frequency will change until it reaches the steady state amount after transition time. All the generators in a microgrid have different frequency values during the transient time. Active power is shared between generators in a way to result same frequency for the whole microgrid generators. Therefore generators active power ratio is similar to their droop gain ratio.

In above equations ω_n and V_n respectively are the nominal frequency (in $^{rad}/_{s}$) and voltage of DG. k_1 and k_2 are droop gains for active and reactive power. By adjusting the reference voltage amplitude and frequency, switching pulses can be determined by pulse width modulation (PWM) switching technic for DGs in the microgrid.

In order to apply droop characteristic and after transforming the measured voltage and current to $\alpha\beta$ reference frame, instantaneous active (p') and reactive (q') power generated by each micro source is calculated as shown in Eqs. (3) and (4). To extract the dc component of the output power, instantaneous powers are passed through a low pass filter (LPF) with ω_c as cut-out frequency.

$$p' = v_{o\alpha} i_{o\alpha} + v_{o\beta} i_{o\beta} \quad (3)$$
$$q' = v_{o\alpha} i_{o\beta} - v_{o\beta} i_{o\alpha} \quad (4)$$
$$P(s) = P'(s).LPF(s) \quad (5)$$
$$Q(s) = Q'(s).LPF(s) \quad (6)$$
$$LPF(s) = \frac{\omega_c}{s + \omega_c} \quad (7)$$

2.2. Virtual impedance loop

Proper operation of droop control in power sharing is due to the inductive characteristic of the generators output impedance and the grid lines. In microgrids the network resistance is not negligible in compare to its reactance. Therefore voltage and frequency of DGs are influenced by both P and Q.

In this paper virtual impedance loop is used to enhance the operation of droop control (Pham and Lee, (2020)). Virtual impedance can be tuned to have a fixed value in different load and networ k conditions. Therefore it is not necessary to verify control parameters in different cases like asymmetric line impedances. The virtual resistance increases the overall damping of the system without power losing.

The main role of virtual impedance is to decouple the active and reactive power control. This will increase the system stability. As it can be seen in Fig. 1, inverter output current

(i_o) is the input of the loop. The output is added to the reference voltage with negative gain. Mathematic representation of the virtual impedance loop is shown by Eqs. (8) and (9) where r_{virt} and l_{virt} are the virtual resistance and inductance values.

$$v'_{\alpha} = r_{virt} i_{o\alpha} - l_{virt} \omega i_{o\beta} \quad (8)$$
$$v'_{\beta} = r_{virt} i_{o\beta} + l_{virt} \omega i_{o\alpha} \quad (9)$$

2.3. Voltage unbalance compensation loop

First step for voltage unbalance compensation is to quantitate the unbalance. According to the IEC standard voltage unbalance is formulated as Eq. (10). VUF should be lower than 2% (Tangsunantham and Pirak, (2013)). To reduce the voltage unbalance, VUF should be calculated by positive and negative sequence components of the output voltage and compared with the maximum threshold. As α and β components of positive (or negative) sequence have equal amplitudes in $\alpha\beta$ frame, the α component of the voltage is used in compensation loop.

$$\%VUF = \frac{V_{\alpha}^{-}}{V_{\alpha}^{+}} \times 100 \quad (10)$$

Voltage unbalance compensation loop is shown in Fig. 2. Voltage positive and negative sequence is passed through absolute value (abs) and low pass filter (LPF) blocks. By calculation of VUF, it is compared with the reference set point which is considered 0.5% in this paper.

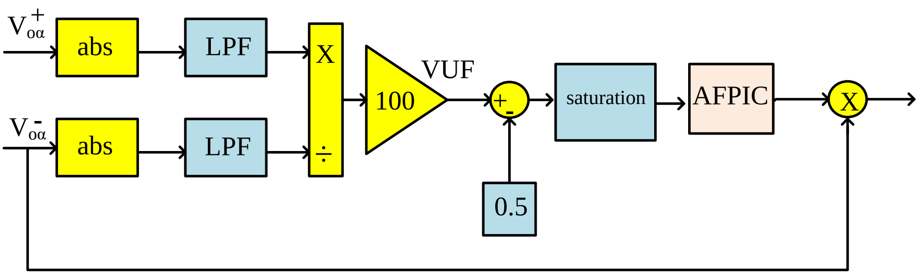

Figure 2. Voltage unbalance compensation loop.

The saturation block is used to bypass the controller, if the VUF is lower that 0.5%. The error signal is reduced by AFPIC. The AFPIC output is multiplied by the voltage negative sequence and finally the compensation signal is subtracted from the droop control output voltage.

2.3.1. Voltage positive and negative sequence detection

SOGI is used to extract the voltage positive and negative sequence (Rodriguez *et al.*, (2007)). Structure of SOGI is shown in Fig. 3 where ω_0 is the resonant frequency and X is a sinusoidal waveform with the frequency of ω. If $\omega = \omega_0$, SOGI operates as an ideal integrator.

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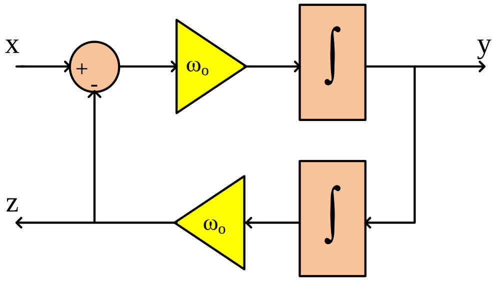

Figure 3. Structure of Second-order generalized integrator.

By applying SOGI as Fig. 4 it operates as a second order band-pass filter. Choosing appropriate k and ω_0 results V_a' which is the main sinusoidal component of V_a. qV_a' has 90 degrees phase lagging with respect to V_a'.

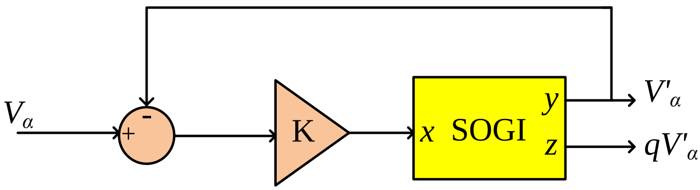

Figure 4. Second order band-pass filter.

To obtain the positive and negative sequence in $\alpha\beta$ and abc frame, the methodology of Fig. 5 is used. Transformation matrix of Eq. (11) is used in this method.

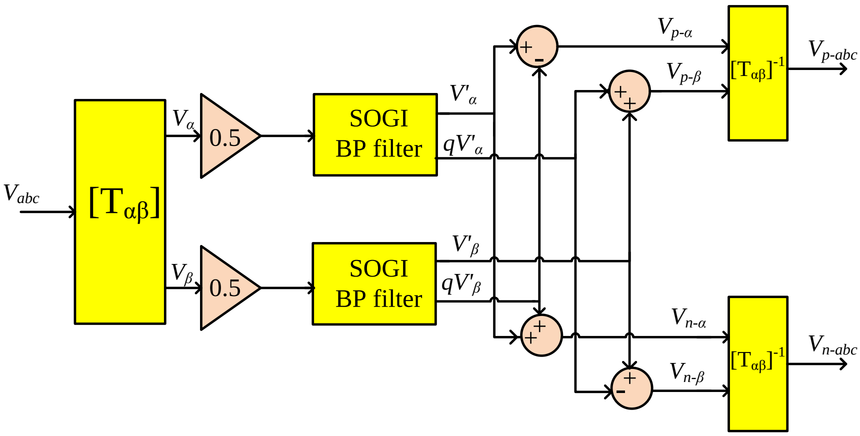

Figure 5. Voltage positive and negative sequence detection.

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$$V_{\alpha\beta} = [T_{\alpha\beta}]\, V_{abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} V_{abc} \qquad (11)$$

2.3.2. Adaptive fuzzy PI controller

The self-adjustment PI controller based on fuzzy logic control (FLC) for voltage unbalance compensation is proposed in this section. Conventional PI controller has low dynamic in complicated, time variant and nonlinear systems. One of the main advantages of FLC system is self-tuning of controller parameters for dynamic processes. Also no parameter estimation is required in designing controller for nonlinear systems. It combines artificial intelligence and control engineering to produce a smart control mechanism (Dong *et al*., (2021)).

Microgrids are dynamic as a part electric distribution network. Due to the large and nonscheduled utilization of one-phase and imbalanced electrical loads, parameters of the voltage unbalance controllers should be verified consequently. In order to have a real time control system, AFPIC is applied to the voltage unbalance compensation loop.

Overall structure of AFPIC is same as the conventional PI controller. Therefore implementing of this system does not have any complexity. Schematic of AFPIC is shown in Fig. 6. FLC is added to conventional PI controller to refine the coefficients K_p and K_i with regard to the error signal and its integral form as two inputs.

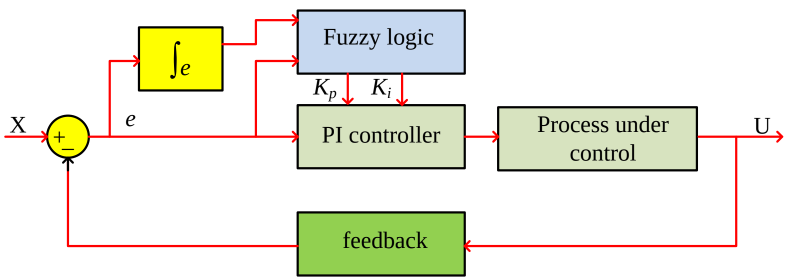

Figure 6. Adaptive fuzzy PI controller.

The triangular membership functions (μ) are defined for input (e and $\int e$) and output (K_p and K_i) variables as they are shown in Fig. 7.

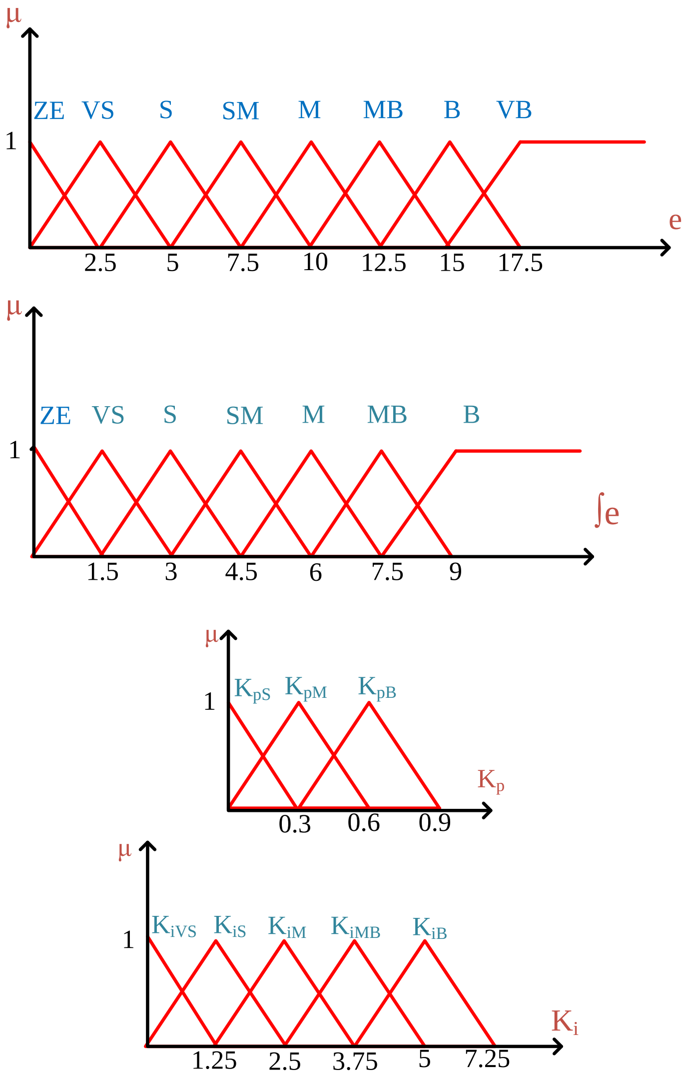

Figure 7. Triangular membership functions of input and output variables in AFPIC.

As the saturation block of compensation loop limits the error to the positive values, input variable membership functions do not have negative quantities. Fuzzy rules are given in table 1 and the abbreviations ZE (zero), VS (very small), S (small), SM (small medium), M (medium), MB (medium big), B (big) and VB (very big) are used to define subsets.

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Table 1. Fuzzy rules table.

$\int e$	e							
	ZE	VS	S	SM	M	MB	B	VB
	$_{i}K/\ _{p}K$							
ZE	$_{bi}K\ /\ _{mp}K$	$_{bi}K\ /\ _{mp}K$	$_{bi}K\ /\ _{mp}K$	$_{bi}K\ /\ _{sp}K$	$_{bi}K\ /\ _{sp}K$	$_{bi}K\ /\ _{sp}K$	$_{bi}K\ /\ _{sp}K$	$_{bi}K\ /\ _{sp}K$
VS	$_{bmi}K/\ _{mp}K$	$_{bmi}K/_{mp}K$	$_{bmi}K/_{mp}K$	$_{bmi}K/_{sp}K$	$_{bmi}K/_{sp}K$	$_{bmi}K/_{sp}K$	$_{bi}K/_{sp}K$	$_{bi}K/_{sp}K$
S	$_{mi}K/\ _{mp}K$	$_{mi}K/\ _{mp}K$	$_{mi}K/\ _{mp}K$	$_{mi}K/_{sp}K$	$_{mi}K/_{sp}K$	$_{mi}K/_{sp}K$	$_{mi}K/_{sp}K$	$_{mi}K/_{sp}K$
SM	$_{mi}K/\ _{mp}K$	$_{mi}K/\ _{mp}K$	$_{mi}K/\ _{mp}K$	$_{mi}K/_{sp}K$	$_{mi}K/_{sp}K$	$_{mi}K/_{sp}K$	$_{mi}K/_{sp}K$	$_{mi}K/_{sp}K$
M	$_{si}K/\ _{bp}K$	$_{si}K/\ _{mp}K$	$_{si}K/\ _{mp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$
MB	$_{si}K/\ _{bp}K$	$_{si}K/\ _{mp}K$	$_{si}K/\ _{mp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$
B	$_{svi}K/\ _{bp}K$	$_{si}K/\ _{mp}K$	$_{si}K/\ _{mp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$	$_{si}K/_{sp}K$

2.4. Voltage and current controllers

The outcome of virtual impedance loop, droop controller and voltage unbalance compensation loop is a reference voltage signal. This reference voltage is compared with the inverter output voltage. According to figure 1, the difference (error) is added to the voltage controller as an input signal. Reference signal of voltage controller is compared with the inverter output current and the error becomes the input of current controller. Output of current controller is the final control signal feeding the PWM of the inverter to generate switching pulses. Voltage and current controllers both include proportional resonant (PR) controller to compensate the error and generate the reference signal.

In voltage and current controllers, droop reference voltage and frequency are fed to generate inverter switching pulses. Both controllers are implemented to reject high frequency disturbances and guaranty sufficient damping for the output filter. Also, inner proportional and integral controllers provide zero steady state error and they improve system transient response.

3. Simulation results

In this section a sample microgrid of Fig. 8 is analyzed in presence of unbalanced load. Proposed control method is applied and the results are compared with the case that there is no controller for voltage unbalance compensation. Also dynamic effectiveness of the AFPIC is shown in the case where the unbalance is increased in the microgrid.

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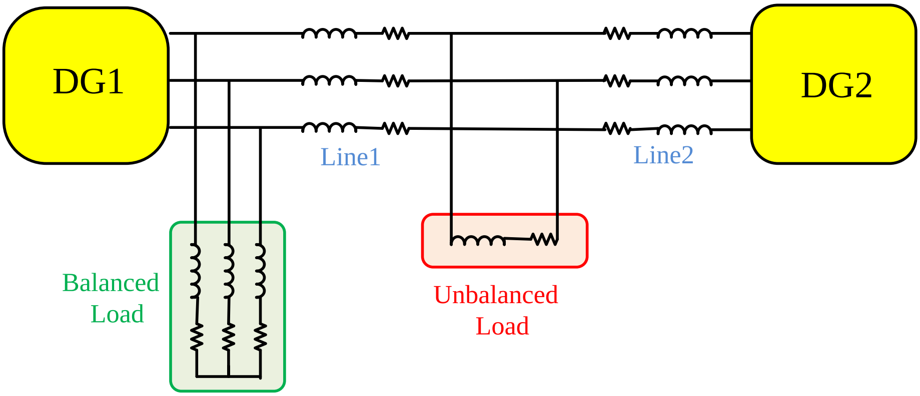

Figure 8. The test microgrid.

3.1. Unbalanced load in the microgrid with conventional controller

At t=1 sec, unbalanced load is connected to the microgrid. VUF is shown for the unbalanced load and two DGs in Fig. 9 (a). It can be seen that after the starting transient and before unbalanced load connection, VUF is zero and there is no voltage unbalance. After switching the unbalanced load VUF percent reaches 3.2, 2.68 and 2.46 for the buses of unbalanced load, DG1 and DG2 respectively. According to IEC standard, VUF over 2% is not acceptable and should be compensated.

The output active powers of DGs are shown in Fig. 10 (a). Although the active power droop gain is same for two DGs, DG1 generates more active power. It shows that with conventional control method, proper power sharing is not satisfied.

3.2. Unbalanced load in the microgrid with proposed controller

Similar to the previous section, the unbalanced load is applied to the microgrid with voltage unbalance compensation loop and AFPIC. VUF is shown for the unbalanced load and two DGs in Fig. 9 (b). The peak of VUF in the transient time is reduced in comparison to the previous case. It shows that the proposed controller has desirable performance in transient time.

In the steady state time the VUF percent has reached 0.8, 0.5 and 0.5 for the buses of unbalanced load, DG1 and DG2 respectively. It can be concluded that the proposed controller has reduced the impact of unbalanced load on the microgrid bus voltages.

Fig. 10 (b) shows the generated active power for DG1 and DG2. It shows that the power sharing performance is also enhanced in the microgrid with proposed controller. Both DGs generate approximately similar active power while having the same droop coefficients. This will increase the frequency stability of the microgrid.

It should be noticed that by increasing the total VUF, proposed method with AFPIC can be easily adapted to the new load condition while with conventional PI controller the system is leading to instability. In order to verify the self-adjustability of the voltage unbalance AFPIC, unbalance load of the previous simulation is %25 increased. Fig. 11 shows the VUF of DG1 for the microgrid with voltage unbalance compensator including conventional PI controller and AFPIC (proposed control method).

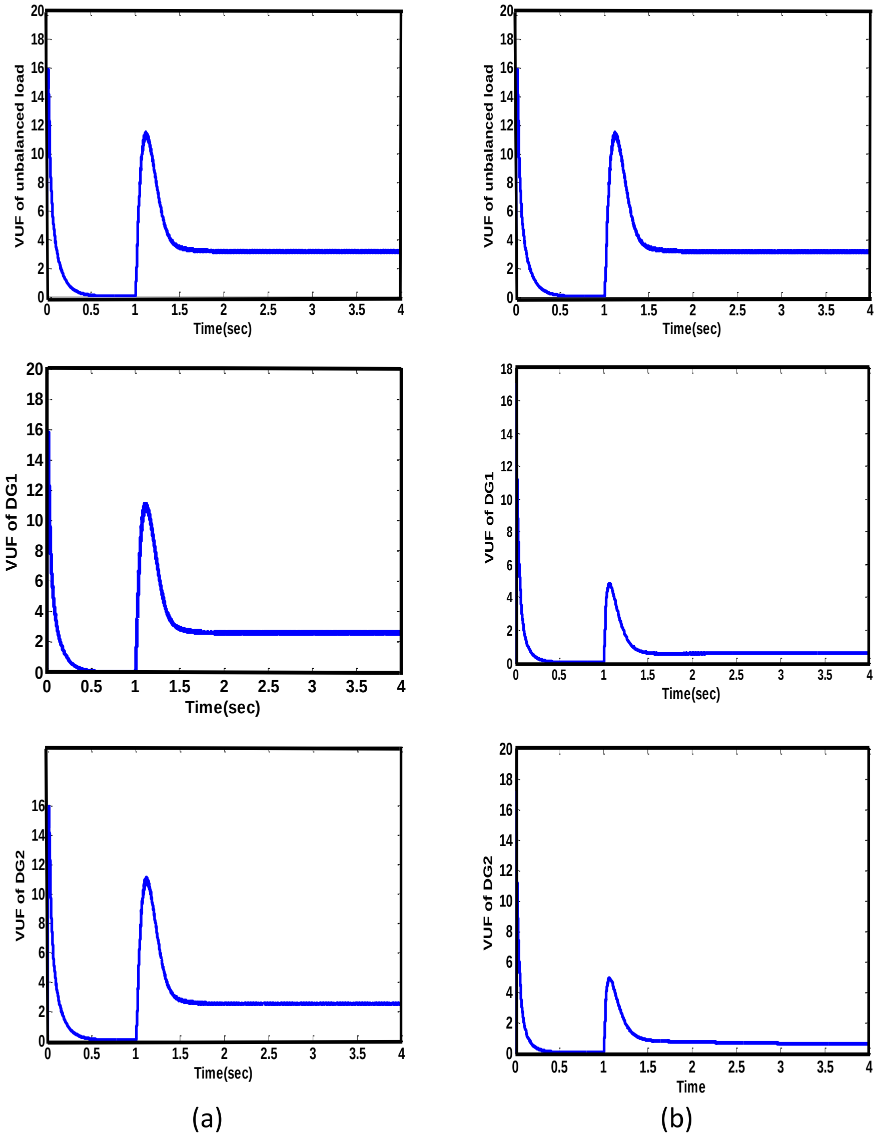

Figure 9. VUF of the unbalanced load and DGs for the microgrid: a) without compensation, b) with compensation.

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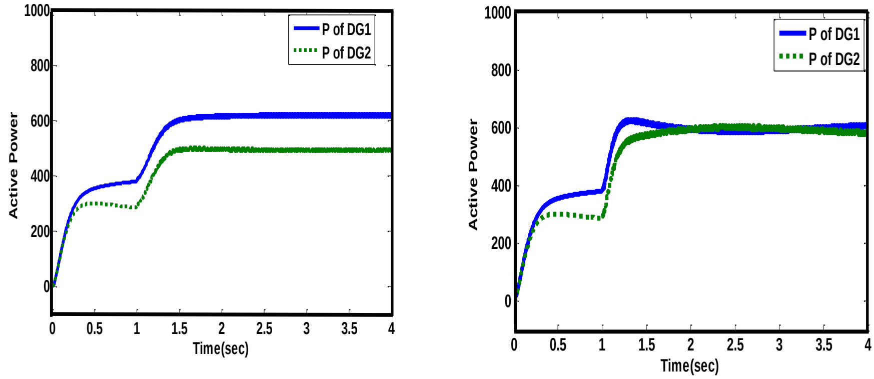
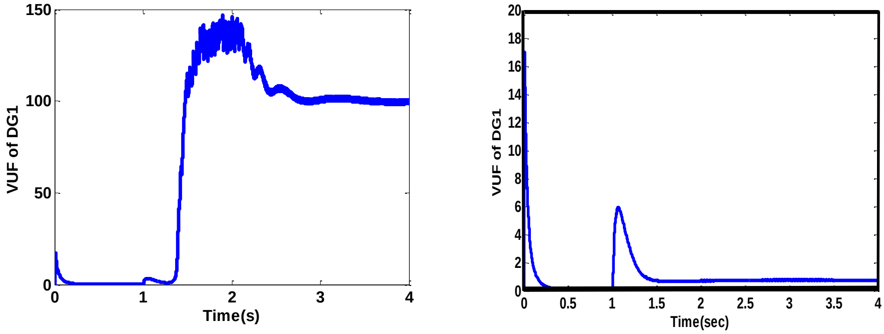


(a) (b)

Figure 10. Output active power of DGs: a) without compensation, b) with compensation.



(a) (b)

Figure 11. VUF of DG1 for %25 increment in unbalanced load of the microgrid with voltage unbalance compensation including: a) conventional PI controller, b) AFPIC.

It can be observed that the voltage unbalance compensator including conventional PI controller is failed not only to reduce the unbalanced load effect on the microgrid but also to maintain the system stability. After connecting the critical load the controller is failed in supplying the negative sequence component of the load current. However the presented control scheme has successfully reduced the VUF for DG1 below the standard threshold.

As it is shown in Matlab simulation results, by applying AFPIC to a voltage compensation loop, the droop control based inverter reference voltage is modified. Virtual impedance loop is combined with droop control to enhance its operation. Also, SOGI is used to extract the voltage positive and negative sequence. By using this method, VUF is maintained below the maximum threshold. The proposed method, has the dynamic capacity of decreasing the VUF value for all kinds of loads.

4. Conclusion

A control approach has been proposed to optimal compensate for voltage unbalance in an islanding microgrid. Droop control method for power sharing with voltage and current controllers is developed by adding a voltage unbalance compensation loop. A self-adjusting fuzzy PI controller is implemented for real time modification of compensating signal which is added to inverter reference voltage in each DG unit. Virtual impedance loop is used in the controller to enhance the power sharing. Proposed method has the capability to be applied to different load operating points without the need for adjustment of controller parameters. A microgrid with a sample single phase load is tested with the proposed control scheme and the obtained simulation results show that voltage unbalance is well compensated.

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