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Stability Analysis of the Micro-Grid Operation in Micro-Grid Mode Based on Particle Swarm Optimization (PSO) Including Model Information

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Authors' contributions

This work was carried out in collaboration between all authors. Author SMM designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors SMS and RD managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

Aims: Create a control policy for improve the quality of optimal voltage - frequency (V-F) power supply and stability analysis in a micro-grid scenario include DG units.
Study Design: Control policy for respond to sudden changes such as starting micro-grid mode, and or in load change conditions was designed.
Place and Duration of Study: IAU, Iran, February 2015-January 2016.
Methodology: This paper with using of particle swarm optimization (PSO), model information analysis, and voltage and frequency stability of a micro-grid is controlled. Proposed controller of model include an inner current control loop and an outer power control loop based on synchronous reference frame and conventional PI regulators.
Results: Simulation results show satisfactory performance voltage and frequency of system. Also, results show that proposed control policies established by acceptable limits voltage and frequency of system, and support from output power per some of DG unit in duration of load changes. In

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addition, simulation results improved system stability under proposed power controller and reduce errors in the proposed controller. The proposed PSO algorithm has good performance for finding the desired optimal control parameters to achieve the control objectives. Thus, automated enforcement mechanism based on the model information has been developed to determine these limits.

Conclusion: The paper is presented a power (V-F) control policy for micro-grid based on PSO algorithm. This is done by proposed voltage and frequency controller based on PSO algorithm for real-time self-tuning. Besides, fast dynamic response and an acceptable level of harmonic distortion as two main basic system performance parameters were obtained. The main objectives are supplied power quality improvement and power stability, otherwise in faced to sudden changes such as transition from connection to grid mode to island mode or load change is located.

Keywords: Micro-grid operation; particle swarm optimization (PSO); model information; micro-grid stability; distributed generation (DG).

1. INTRODUCTION

Now, climate changes concerns in the energy sector have shifted towards a new field from modern power grids. The rapid increase in load demand can be create in faced widespread with power generation units that called distributed generation (DG) units. These units can be operated either parallel to the main grid (grid-connected mode) or as the standalone (micro-grid mode). Micro-grid (MG) can be considered as a new innovation for a small-scale power generation grid defined that group of DG units using power electronic devices such as voltage source inverter (VSI) system aggregated. This scenario arises for power grid complementary infrastructure in the face of load demand rapid changes. Extensive infiltration on market micro-sources such as wind, solar, hydro and fuel cells replace which are cause green and sustainable energy and stable development for power grid [1]. Usually these resources by pulse width modulation systems - voltage source inverter (PWM–VSI) is connected to the power system that include nonlinear voltage characteristics connected to semiconductor components and generate high switching frequency and quality of end users power supply are affected [2].

In addition, there are three main factors that effect on micro-grid operation characteristics. The first type of DG units connected to the grid. The second is related to the type alternative current/direct current (AC/DC) PWM-VSI system. Usually, these are connected for communicate with the main types of DG units or directly connect to a user load, and MG operation affects through lack of physical inertia, generate harmonic distortion, increase system dynamic band, and limitations in their ability in overload. Third is control loop that for DC/AC PWM-VSI system used. Mainly, MG operation is controlled by the VSI system, so efficient control loop for reliable operation seems necessary [3]. The interactions between all these components leads to temporal changes in the power characteristics supplied to customers. Mainly, power quality as short to long periods of disturbance or outage occurs in output power characteristics [4].

The serious issues effect on power quality and stability can be classified based on MG operation mode. In the grid-connected mode, MG connected to distribution network and distribution network play role as Slack bus. In this mode, no longer need to control voltage and frequency but in micro-grid mode, MG is independent of external grid and control system for voltage and frequency stability is required. This mode increases the reliability and proper division of power between units. In the micro-grid mode, voltage and frequency profile should be created by MG, otherwise the system due to sensitivity of connected DG unit and the power converter applications will collapse [5]. Besides, output waveform harmonic distortion is an important issue that often is caused by the inverter switching high speed. Long-term transient period can affect all the equipment without having to put it in island operation mode and or occur in during load changes [6]. As well as, in the micro-grid mode, system should provide controlled voltage and frequency with low power quality that may occur. So, voltage and frequency regulation should be considered as main control objectives, while power flow can be embedded through DG units to be managed faced with total load demand. Otherwise, the system had to load collapse. So, the power sharing in the MG can establish optimal use of DG units, including the rate of inverter. For these reasons, the power control loop in DG unit based on inverter to maintain power supply quality and power stability improvement is necessary. In addition to the power control loop and without of micro-grid operation mode, also it is necessary that an inner current control loop to create the VSI system to act as a current source amplifier. This ensures that there are precise detection and occur short transient state for inverter output current. Also, synchronization method for matching inverter performance is mandatory for each MG operation mode. Just as for implementation a reference frame in control scheme is required [7].

In the paper, optimal control policy of power is proposed for the VSI system based on DG unit in automated MG operation mode according to real-time self-tuning method. Aim of this controller improve supplied power quality and the stability by connected DG units. The voltage and frequency regulation, dynamic response, steady state response and harmonic distortion are the main performance parameters that specially, when MG is located in load change conditions or micro-grid mode is considered. The controller scheme consists of an inner current controller loop and outer power controller loop based on a synchronous reference frame and conventional PI regulators. Power controller for voltage-frequency (VF) control mode is designed. As well as, in the paper, PSO algorithm for adjust real-time self-tuning power control parameters applied. The proposed policy express when MG is under micro-grid mode or change load conditions, DG unit itself in order to adjust frequency and voltage of system in (V-F) control mode adapted. In result, researchers in this paper have managed with power (V-F) stability analysis in micro-grid operation mode and providing the requirements of a power control policy guarantee high performance operation in dealing with power quality and stability requirements and reduce errors in proposed controller.

The paper has been categorized as follows; the model problem expressed in power (V-F) control mode for automatic and micro-grid mode has been evaluated in part two. The simulation results of PSO optimization algorithm and its analysis have been presented in part three. The conclusion has been presented in part four.

2. PROBLEM STATEMENT IN VOLTAGE AND FREQUENCY POWER CONTROL MODE FOR AUTOMATED MICRO-GRID MODE

In this section, optimal power control policy is proposed for VSI system based on DG unit in automatic micro-grid operation mode according to real-time self-tuning method. The purpose of this controller is improved the stability and supplied power quality by connected DG units to the micro-grid. When MG is located in load change conditions or micro-grid mode, voltage and frequency regulation, dynamics response, steady-state response and harmonic distortion are the main performance parameters.

2.1 Three-Phase VSI Grid-Connected System Modeling

The conventional three-phase VSI model connected to grid with an LC filter in Fig. 1 is shown. R_s and L_s are respectively equivalent resistance of node and connection transformer filter inductance if applicable and so that network is detected by inverter. Besides, C, C_1, C_2 all are filter capacitor, L is inductance and V_s is voltage of network.

In equivalent circuit reference frame system based on state space equations [8] has been proposed to this form:

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \left\{ \frac{R_S}{L_S} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{1}{L_S} \times \left(\begin{bmatrix} V_{Sa} \\ V_{Sb} \\ V_{Sc} \end{bmatrix} - \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \right) \right\} \quad (1)$$

Using with Park's transformation, equation 1 can be expressed in reference frame as follows:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \left\{ \begin{bmatrix} -\frac{R_S}{L_S} & \omega \\ -\omega & -\frac{R_S}{L_S} \end{bmatrix} \times \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L_S} \times \left(\begin{bmatrix} V_{Sd} \\ V_{Sq} \end{bmatrix} - \begin{bmatrix} V_d \\ V_q \end{bmatrix} \right) \right\} \quad (2)$$

In which, ω is the related angular frequency. Park's transformation can be defined as follows:

$$\mathrm{i}_{dq0} = \{ T \times i_{abc} \} \quad (3)$$

Where,

$$\mathrm{i}_{dq0} = \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}, \quad \mathrm{i}_{abc} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (4)$$

$$T = \frac{2}{3} \times \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (5)$$

In which, $\theta = \omega_s t + \theta_0$ is synchronous rotation angle, and θ_0 represents the initial value.

The control system are looking for supply a set of characteristics in terms of measurable quantities that identifier performance of system. Some of these parameters represents a system performance, such as ($M_p, t_r, t_p, t_s, \ldots$), and the steady error (e_{ss}) are introduced, which must be achieved at the same time. In conventional mode, control method are caused by trial and error method. Now, in the paper by introducing a system performance indicator and achieve to optimal set of system parameters through minimizing the system functions can be reached to optimal and stable system results (according to the requirements of appropriate performance indicator). According to the control objectives, mainly minimizing error integral function problem related with four measuring error includes: integral absolute error (IAE), integral square error (ISE), integral time square error (ITSE), and integral time absolute error (ITAE) that best results of previous studies is related to using (ITAE).

$$F = Min\left\{\int_0^t t\left|e(t)\right| dt\right\} \quad (6)$$

Where t is the time and $e(t)$ is the difference between set point and controlled variable. In conclusion, the controller objective function in the paper, formulated based on the ITAE which calculated with using Simpson's $\frac{1}{3}$ rule.

2.2 VSI Control Policy in Micro-Grid Mode

The DG unit can be classified into three types of energy source. The source with variable speed (variable frequency) such as the wind energy, source with high speed (high frequency) such as the micro-turbine generators, and direct energy conversion source such as the fuel cells and photovoltaic. For this reason, it is necessary to use from the VSI as a DG unit interface to grid and providing flexibility operation [6]. As shown in Fig. 1, the power circuit VSI unit based on DG is associated with a control structure, thus controlled operation of DG unit is based on inverter control mode. For example, expected in

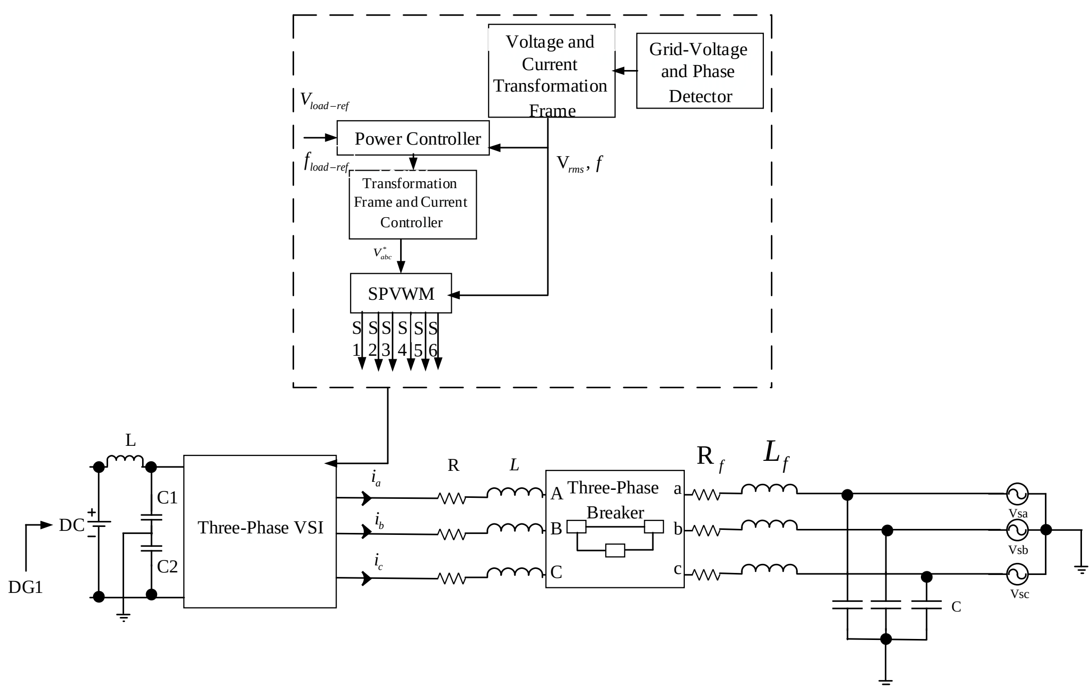

Fig. 1. Three-phase VSI model connected to grid

micro-grid mode, the DG units with considering power quality supply source are responsible respond to the load demand. In this case, voltage and frequency is not fixed, and inverter must the (V-F) control mode with regard to inverter power rate for power sharing problems can be pursued [9]. Thus, in appropriate power control mode can be effective in operation with high performance of DG unit. The following sections most appropriate power control policy provide for micro-grid mode.

2.2.1 Voltage and frequency control policy

It is essential for reliable operation of MG to ensure lack of transfer between micro-grid mode and also maintain stable operation in during of the micro-grid mode with according facing to load demand are provided regulation voltage and frequency conditions. In this case, the DG units must affected the load demand, voltage and frequency stabilize with collapse constraints so that (V-F) control mode by DG unit to resolve mentioned requirements to be established [10]. Its block diagram can be seen in Fig. 2.

Because the reference of voltage and frequency values can be defined in form locally or by micro-grid control center, frequency can have been calculated by phase locked loop (PLL) application and V_{rms} that is expressed in [11].

2.2.2 Proposed control policy

This section offered proposed power controller policy for three-phase the VSI system grid-connected. In Fig. 3 the proposed power controller schematic is shown.

In Fig. 3, the controller schematic are include three main block diagram: power controller, linear current controller, and PSO algorithm for real-time self-tuning of power control parameters. The controller schematic include one current control inner loop and power control outer loop based on a synchronous reference frame and conventional PI regulator. The power controller is designed for power (V-F) control mode.

2.2.2.1 Power control policy

The purpose of this policy, improved power supply quality taking into account control mode objective. The left side shows proposed power controller based in PI regulators block diagram. This controller provides an external control loop that is used to generation reference vectors i_q^*, i_d^*. In conclusion, a relatively slow change of reference current path ensures output power high-quality of inverter, that symbol of control objective. In this paper, the (V-F) control policy based on PSO algorithm is proposed for VSI based DG unit. The voltage and frequency of system are main control objectives that should to calculate in during micro-grid operation mode. This policy for respond to sudden changes such as the starting micro-grid mode, and or in change load conditions was designed. In this case, voltage and frequency controller is based on adjustment their reference values (V_{ref}, f_{ref}) and PSO provided a smart process for optimal control parameters in order to release qualified reference current vectors. Accordingly, in the reference frame dq and according to two PI regulators reference current vector so as is presented:

$$i_d^* = \left\{ (\mathrm{V}_{ref} - V) \times (\frac{\mathrm{K}_{pv} + K_{iv}}{\mathrm{s}}) \right\} \qquad (7)$$

$$i_q^* = \left\{ (f_{ref} - f) \times (\frac{\mathrm{K}_{pf} + K_{if}}{\mathrm{s}}) \right\} \qquad (8)$$

2.2.2.2 Current control policy

The controller objective is ensuring from accurate tracking and short transition from inverter output current. In the right side, current control loop block diagram has been designed based on a synchronous reference frame. The linear current controller based space vector pulse width modulation (SVPWM) and type of open loop voltage using internal current feedback loop. Usually, this controller in cases where applied voltage to resistance–impedance (R-L), so that impulse current in inductance are used to minimize errors. To detect voltage phase angle in order to implement the Park's transformation in the control schematic, it is necessary to use PLL block. Two PI regulator to eliminate current error, and both inverter current loop and voltage feed forward loop network to improve steady state and dynamic performance are used. In conclusion, controller output signals is indicative reference voltage signals in frame dq. These are obtained by the inverse Park's and Clarke 's transformation, so that reference voltage signals generation controller in stationary frame $\alpha\beta$, uses from mixture six-pulse insulated gate bipolar transistor (IGBT) SVPWM for inverter. In addition, using with SVPWM method guarantees that desired output voltage vectors controller is obtained with less harmonic distortion.

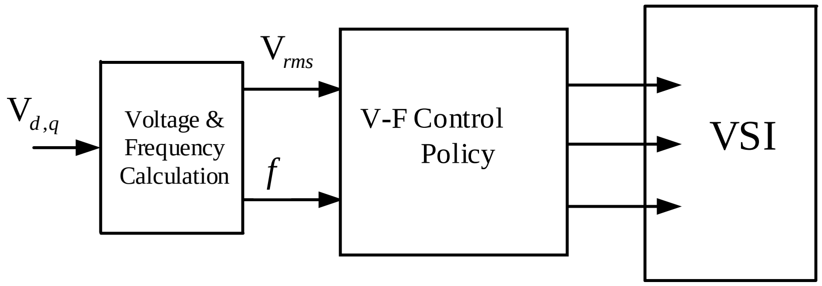

Fig. 2. VSI controller based V-F power

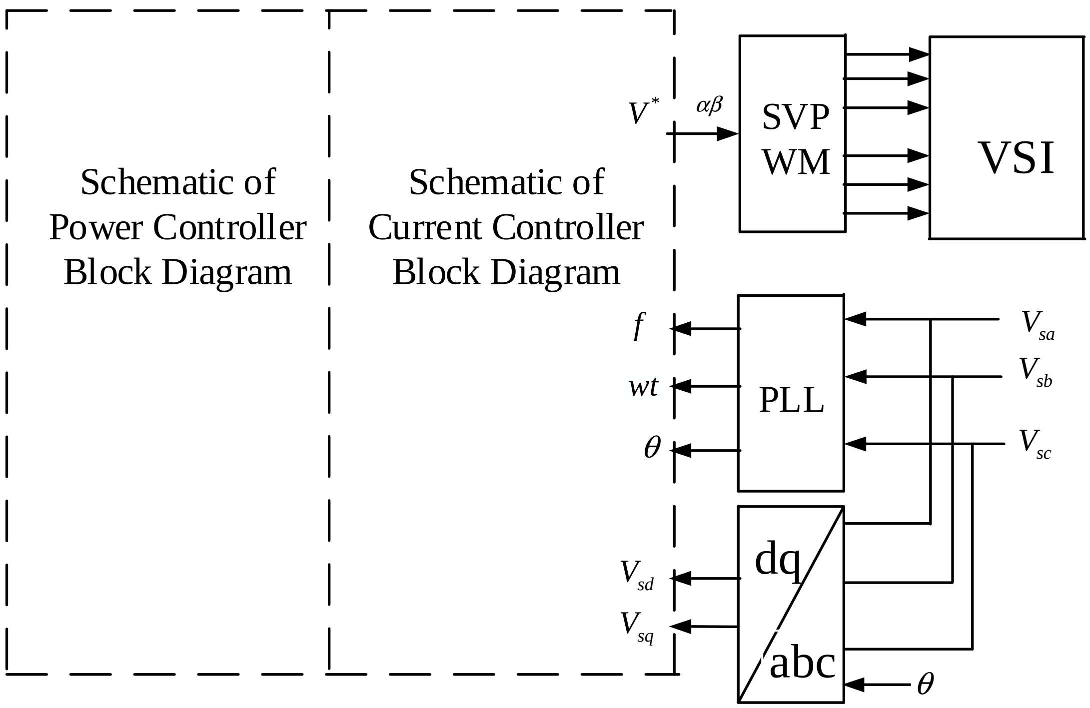

Fig. 3. Proposed power controller schematic

In synchronous frame dq, according to equation 2, reference voltage signal thus are presented.

In which in equation 9, asterisk "*" it points to reference values, reference is indicative $\frac{dX_d}{dt} = i_d^* - i_d$ and $\frac{dX_q}{dt} = i_q^* - i_q$. With using the Clark's transformation equation 10 can be transferred to the stationary frame is determined as follows:

$$\begin{bmatrix} V_d^* \\ V_q^* \end{bmatrix} = \left\{ \begin{bmatrix} -K_P & -\omega L_S \\ \omega L_S & -K_P \end{bmatrix} \times \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} K_P & 0 \\ 0 & K_P \end{bmatrix} \times \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} + \begin{bmatrix} K_i & 0 \\ 0 & K_i \end{bmatrix} \times \begin{bmatrix} X_d \\ X_q \end{bmatrix} + \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} \right\} \quad (9)$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \left\{ \frac{2}{3} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \times \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \right\} \quad (10)$$

In addition, inductance current is obtained using a low-pass filter (LPF). In the paper, LPF as a first order transfer function is considered [11].

3. SIMULATION RESULTS

For optimize control parameters and reduce control error are used from PSO algorithm due to its many advantages over other optimization algorithms. The PSO algorithm method is based on smart computing that to solve problems (LP, NLP, ILP ...) are recommended [12-14]. Three phase VSI system model and proposed controller with using MATLAB/Simulink environment, simulated and identified in Fig. 1. As well as, the PSO algorithm by M-file program implemented in MATLAB. Model parameter include: $L_s = 5mH, R_s = 1\Omega, f = 50\,Hz$, filter capacitor is $50\mu F$, input capacitor toward DC is $5000\mu F$, power rate of DG unit is $5000Kw$, and current control parameters are $K_p = 12.6$ and $K_i = 0.002$. Also, for the SVPWM based on current controller, sampling switching and frequency are respectively $10kHZ$ and $500kHZ$. Besides, the PSO algorithm parameters (maximum iterations to achieve the optimal solution: 500 iterations, and number of sampling: 200 particles) has been defined. As shown in Fig. 3, the system under study overall structure includes a DG that in form of a battery have been modeled and is connected to a network by switching method. In this figure is used from consumption load in the network structure. Also, it has the circuit breaker to connect and disconnect to bus infinite (switching time is between 0.3 to 0.4 seconds). As well as, in Figs. 2 and 3 represent the power, voltage and current of under study network and switching system overall structure of the network with generation pulse is shown respectively. According to the network, do sampling from voltage and current under study network and finally switching pulses is determined by the control structure [15]. All results in terms of per unit ($p.u.$). Accordingly, applied software simulation and with using the PSO algorithm following result has been obtained. In Fig. 4, the junction location of DG voltage changes is shown.

According to Fig. 4, in times of 0.3-0.4 second system loses global network supporting. In this conditions, lack of global network presence in network caused by disturbed power balance. According to the results, optimized controller by classic controller (purple wave form) in this situation, has better control on voltage variations and less fluctuations. In Fig. 5, DG output current changes is shown.

In according Fig. 5, since that in times of 0.3-0.4 second, system loses global network supporting, the DG current is increased. In the meantime, the optimized controller by the classic controller has most desire situation in current fluctuation and less fluctuation compared with PI classic (conventional) controller.

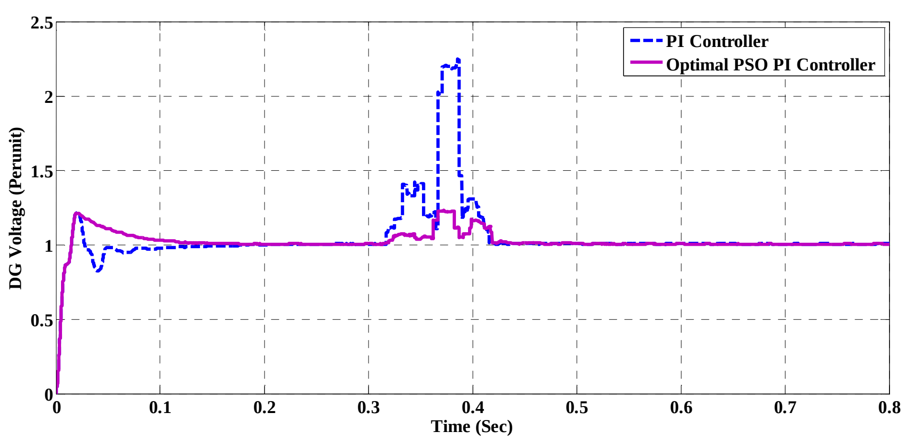

Fig. 4. DG output voltage changes in the presence of the PSO algorithm

Also, Fig. 6 is shown generated output active power changes of DG.

In according Fig. 6, in condition that optimization is done (blue curve), result compared with don't optimization mode (purple curve) have a difference and there are less active power fluctuations compared in optimization case with non-optimization case.

In Fig. 7, is shown network reactive power changes with using the PSO algorithm and conventional mode.

In Fig. 7, the output reactive power fluctuations of DG (blue curve) in optimized controller mode greatly reduced and more desirable. This fluctuations is variable between 0-1 p.u. but in PI conventional controller mode without presence of the PSO algorithm (purple curve) between 0-0.2 p.u. is variable.

In Fig. 8, the network voltage changes in conditions the presence of the PSO algorithm and without applying it is shown.

In according Fig. 8, the PSO algorithm by changing control parameters attempted to optimize the voltage profile and causes that decrease voltage fluctuation (purple curve).

In Fig. 9 is shown network output current changes in presence of the PSO algorithm and without presence of it.

As is clear in Fig. 9, in times of 0-0.2 second in the applied optimize mode with the PSO output result (purple curve) compared with don't applied optimize mode (blue curve) is occurred less fluctuations.

In Fig. 10, the global network active power changes are shown.

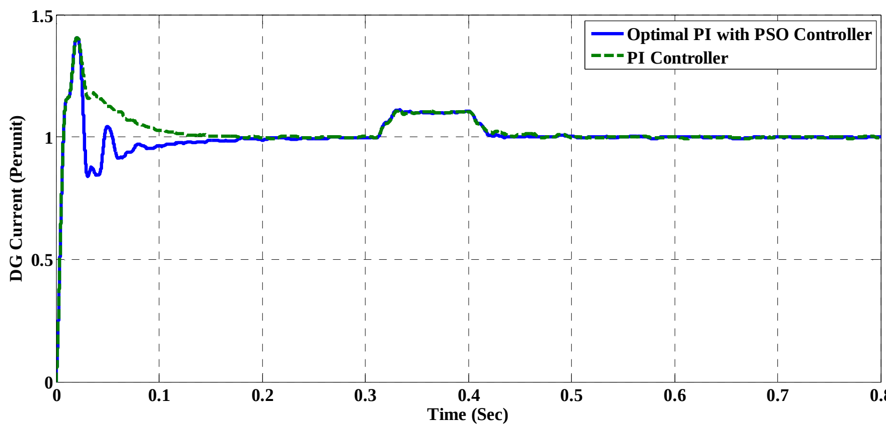

Fig. 5. DG output current changes

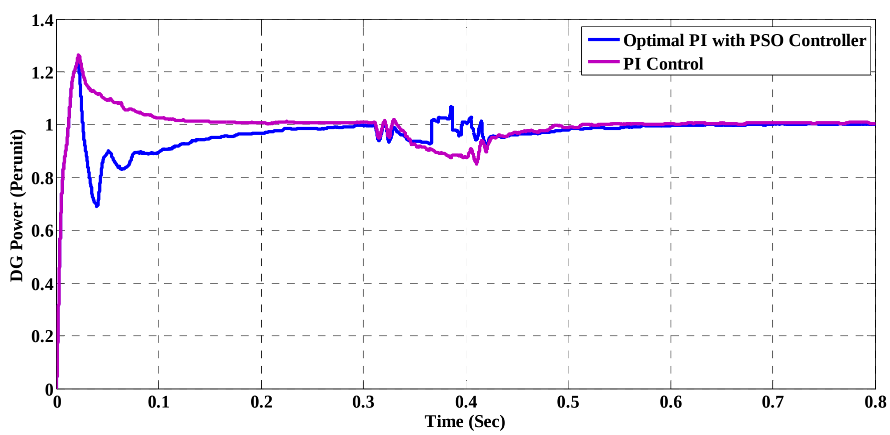

Fig. 6. The generated output active power changes of DG in presence of the PSO algorithm

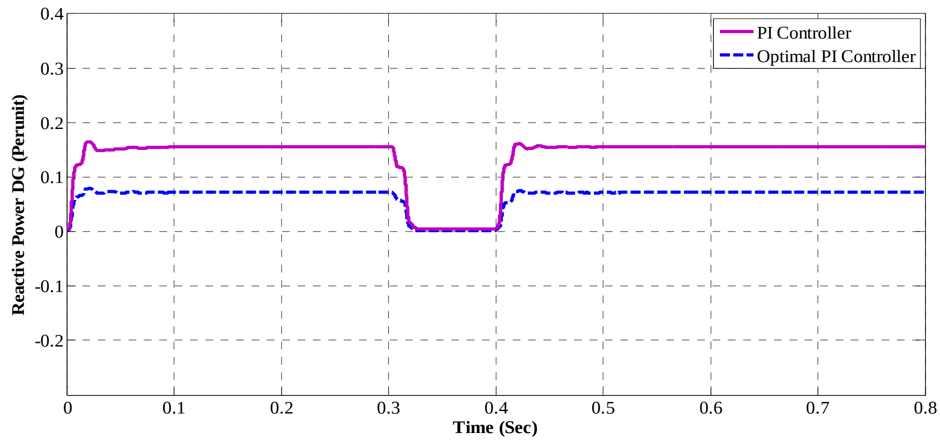

Fig. 7. The network reactive power changes of DG in presence of the PSO algorithm

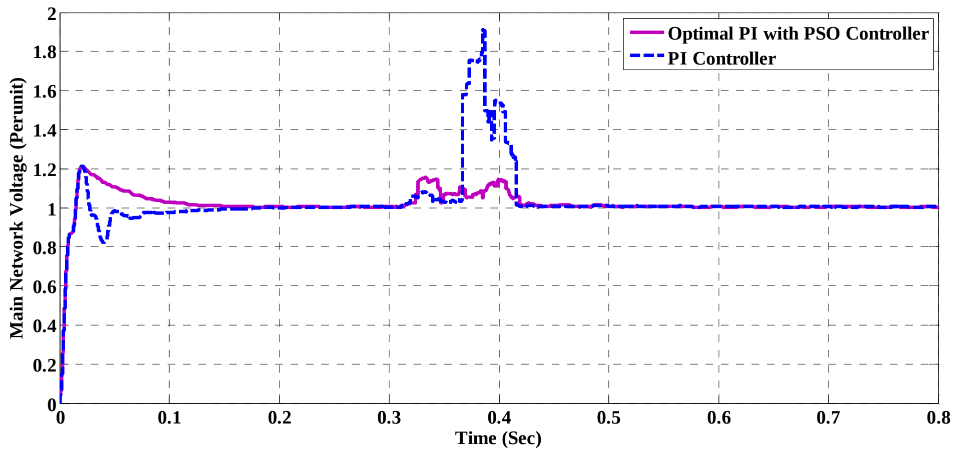

Fig. 8. The network voltage changes in presence of the PSO algorithm

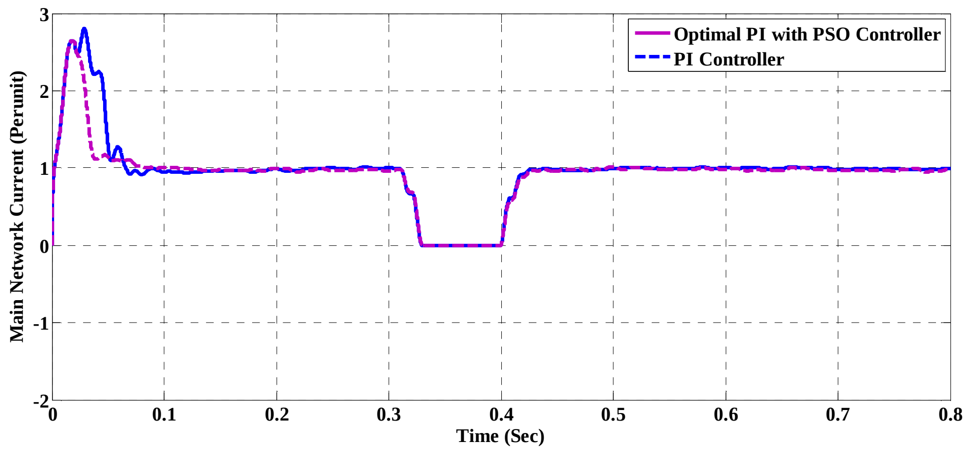

Fig. 9. The network output current changes in presence of the PSO algorithm

Due to network conditions power changes have been reduced. As is clear in Fig. 10 in times of 0-0.3 second in the applied PSO algorithm situation, the main grid power result (purple curve) compared with don't applied PSO mode (blue curve) include improved fluctuations and is caused minimal changes. Also, in Fig. 11, the network reactive power changes is shown.

According to Fig. 11, in condition that system with using the PSO algorithm is caused to changes and amount of reactive power is reduced and arrive from 0.3 to 0.15 p.u. (blue curve).

In Fig. 12, the network frequency changes under study are shown. In Fig. 12, frequency variations is shown with two modes the PSO algorithm and classical methods. In this figure, the frequency variations in optimized controller mode is variable between 49.57 to 50.05 hertz (Hz) (blue curve) but in without presence of the PSO algorithm is variable between 49.8 to 50.3 Hz (purple curve). This is indicated frequency variations with using the PSO algorithm is more limited and in conclusion result is more desire. In Fig. 13 is shown the network harmonic spectrum in condition that is used classic controller.

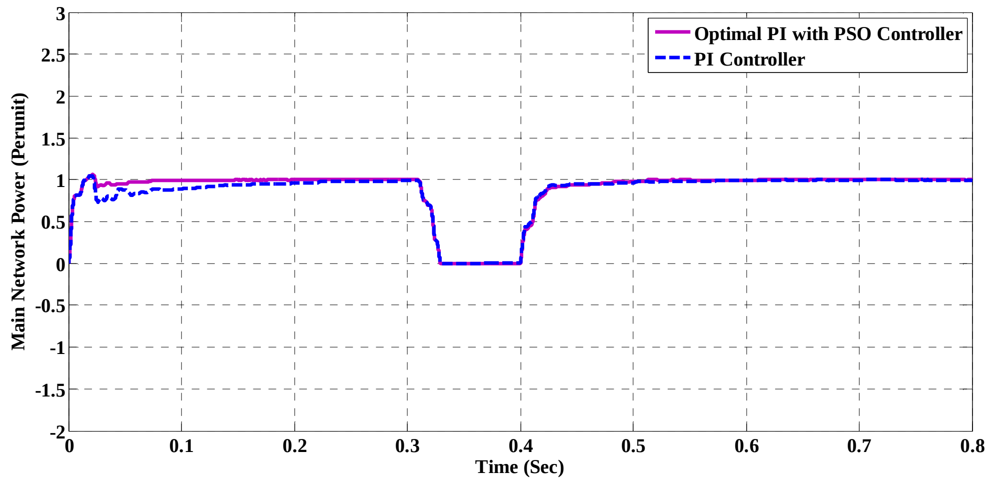

Fig. 10. The global network active power changes with presence of the PSO algorithm

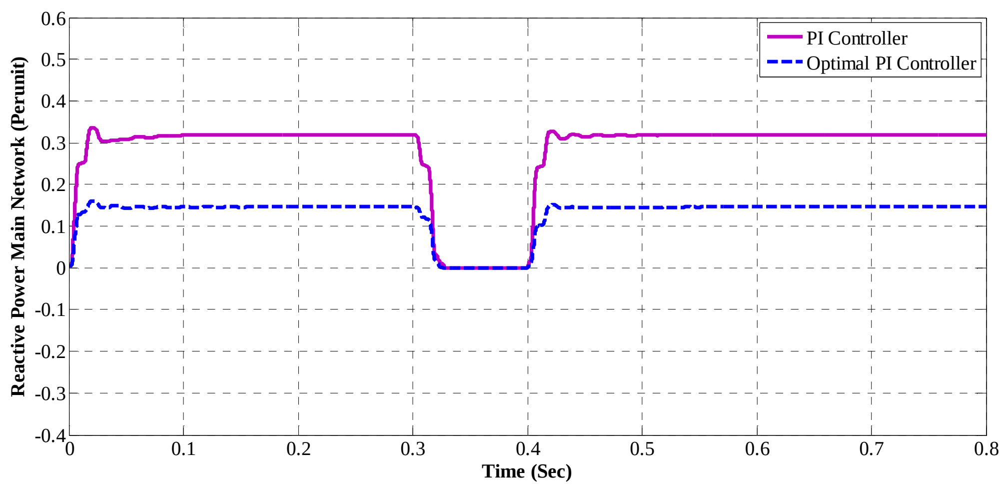

Fig. 11. The global network reactive power changes in presence of the PSO algorithm

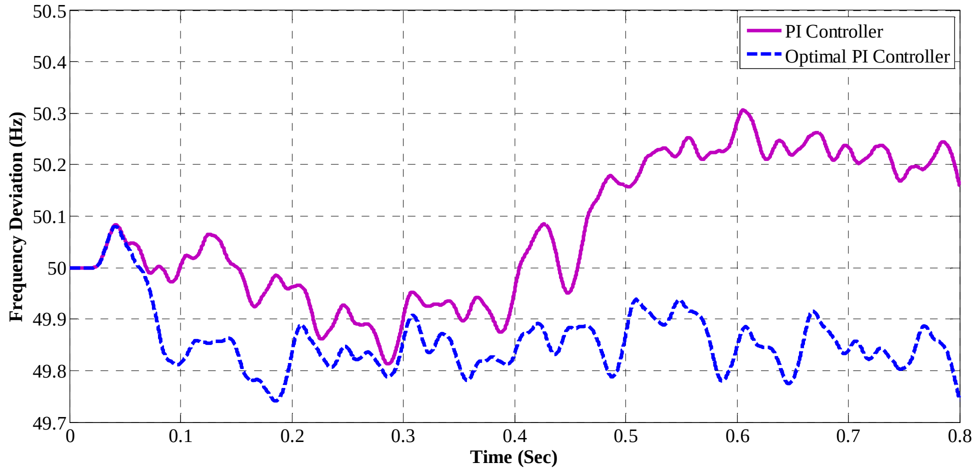

Fig. 12. The network frequency changes in presence of the PSO algorithm

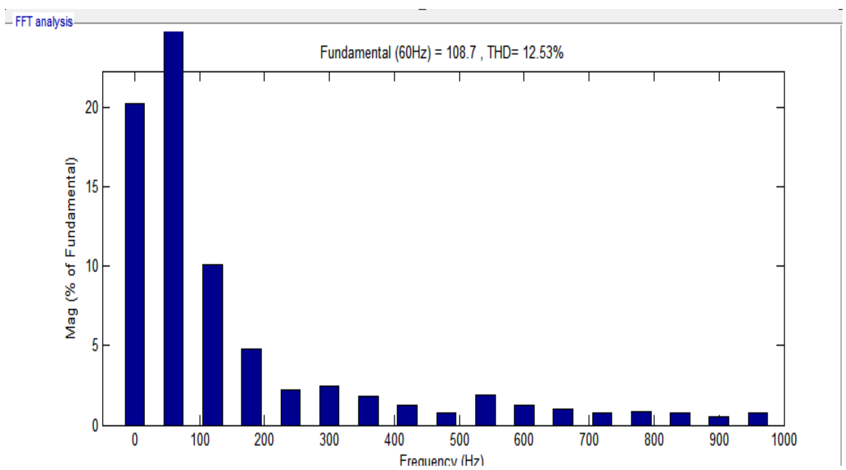

Fig. 13. The network harmonic spectrum with using the classic controller

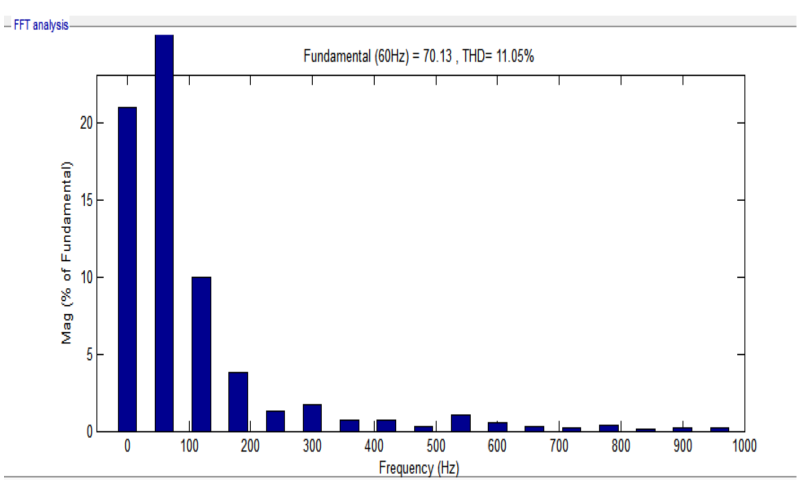

Fig. 14. The network harmonic spectrums with using the optimal classic controller

In Fig. 13, in this conditions total harmonic distortion (THD) is 12.53 percentage. This number by the optimal classic controller is reduced to 11.05 percentage.

As well as, in Fig. 14 is shown harmonic spectrums obtained from PSO algorithm.

In according to Fig. 14, THD is obtained with using the optimal classic controller 11.05 percentage that compared with THD in without in presence of the PSO algorithm condition is reduced about 1.5 percentage.

4. CONCLUSION

The paper is presented a (V-F) power control policy for micro-grid based on the PSO algorithm. Aim of this work, power quality maintenance and stability improvement in faced to load demand in micro-grid island operation mode. The voltage and frequency control of systems for DG unit based inverter in automated micro-grid mode applied. This is done by proposed voltage and frequency controller based on the PSO algorithm for real-time self-tuning. Also, fast dynamic response and an acceptable level of harmonic distortion as two main basic system performance parameters were obtained. Also, the PSO algorithm to solve optimization problem arising from the need to find the optimal parameters for proposed power controller. This algorithm is planned for optimization problems processing based on the error in real-time. Also, for each control objective, exclusively implemented separately. This algorithm performance provides accurate results that the approach is consistent optimization problems in many the engineering applications.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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