International Journal of Systems Signal Control and Engineering Application 9 (3-4): 66-74, 2016
ISSN: 1997-5422

Robust Voltage Control of Parallel Inverters in Islanded Microgrids

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Abstract: Today, according to the limitations related to fossil fuels and efforts to reduce use of these resources, countries are focused on using renewable resources. Energy efficiency management can't be created by itself and under effect of the balance between supply and demand of energy and it is necessary for the governments and policy making authorities to use adequate strategies to achieve it. The main strategy using by countries with good achievements in this field is use of concept of Distributed Generation (DG). Increased presence of DG resources in power systems has led to creation of a new structure called microgrids. In this study, the main purpose is to evaluate performance of solar and wind DG resources under normal and islanded conditions. The method presented in this study is based on observation and chaos method in combination with the sliding mode controller and obtained results are considerable.

Key words: Distributed generation resources, microgrid, islanded performance, sliding mode controller, considerable

INTRODUCTION

Advancement and development of industrial societies has been achieved in wide scale through using energy and energy is a political and economic instrument, on which security of all countries is depended. Environmental pollution as a result of combustion of fossil fuels and increasing acceleration toward ending energy resources are two big crises for the current societies. Worldwide changes in field of considering protection of environment and perishability of fossil fuels has accelerated tendency to use renewable energies and is gaining many attentions as time goes. The most important determinant factor in this field is saving time. Today, Distributed Generation (DG) resource has been emerged as a modern technology in power system. Maybe closeness to the consumption place and utilizing it in emergency can be the reasons for using it; although these resources must be considered useful mostly because of use of renewable energy resources such as solar and wind energies. Now a days, density of presence of tiny renewable energy resources such as solar and wind cells is being increased in distribution levels day by day. Such increase in presence of renewable energy resources has led to creation of a new structure in distribution systems called microgrid. Every microgrid is composed of several tiny electric power generation sources which are responsible for supplying local loads (Lasseter, 2002). In sensitive places such as business and industrial buildings and hospitals that are usually with low inertia and their total disposable load is below 1 MW, existence of a backup generation is necessary for blackout times. In this field, if the distribution system is disrupted for any reason and power is not reached to consumer or is gone below international standards, protection systems would be activated and the microgrid is separated from the distribution system and is responsible for supplying power for sensitive and resistant local loads (Katiraei *et al*., 2005; Salam *et al*., 2008). DG resources in microgrids can contain Solar cells, wind generators, micro-turbine and other resources, along with energy savers such as batteries, flywheel and power capacitors (Marei *et al*., 2004). Despite to abundant advantages such as reducing environmental problems, reduce costs of building new power plants, increased system reliability, increase efficiency by reducing transmission losses and reducing congestion on distribution feeders, microgrids have caused new problems in distribution systems (Salam *et al*., 2008; Diaf *et al*., 2008). Among these problems, one can refer to changes in power flow, high-frequency harmonic increase due to use of power electronic devices and fluctuations in frequency and voltage. Microgrids are connected to main grid in common coupling point by a power key and each DG unit is also connected to microgrid by an electronic power electronics interface at the point of common coupling. The basis for

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designing microgtids should be in such manner that it can continue feeding charges in both modes of connected and disconnected from main grid.

Detachment of a microgrid from main grid sustainably and in such manner to prevent creating problem for users is one of the main problems for designers of microgrids. Hence, one of the most important issues in this field is controlling microgrid resources, especially in islanded mode. For this purpose, the resources should control voltage and frequency of system and share a collection of charges among themselves. Therefore, microgrids should have capability of quick management of changes in power and frequency in the network, even in cases that generated power is below required amount by users. As it was mentioned, power electronic devices like inverters could be used to connect DG resources to users. In grid-connected mode, common point voltage in microgrid is supported by the main network. In this mode, types of available algorithms are used to track maximum power of the mentioned point and in islanded mode; DG units compensate voltage and frequency because of lack of voltage. Hence, in this mode, special methods have to be used to control and stabilize voltage of network. It should be also mentioned that traditional methods to control voltage of parallel inverters in islanded mode such as closed loop voltage control using PID and open loop using proportional-resonator controller have many disadvantages such as Create harmonics, frequency deviation and voltage instability which can affect performance of power system directly (Lasseter *et al*., 2002). Hence, an adequate alternative controller is needed such as robust Sliding Mode Controller (SMC) in islanded mode to be used for good performance of inverter in types of nonlinear charges.

Many controlling methods have been presented so far to control performance of parallel inverters connected to DGsources such as solar and wind cells in form of microgrid. Because of problems with these methods, this study is aimed in presenting an adequate and robust voltage controller under title of sliding mode controller based on type PWM.

DG sources based on inverter are main part of DG sources. In these sources, a power electronic interface is used that is usually a PWM inverter with high switching frequency and an outlet filter to weaken harmonic components resulted from switching process (Marei *et al*., 2004). To chase commands of source of power and to achieve high quality electric energy in outlet of inverter sources, it is required to use a suitable current/voltage control system for power electronic interface of these sources. For this purpose, controlling methods with different structures are introduced for power electronic interface of these sources (Marwali and Keyhani, 2004; Kukrer, 1996; Majumder *et al*., 2009; Green and Prodanovic, 2007; Ito and Kawauchi, 1995; Hatziadoniu *et al*., 2003). Under conditions that invertor source is connected to a grid with current control strategy; usually a self-filter is used to limit output current of source. However, to couple these sources to weak grids, to preserve quality of output current and bus voltage of coupling point, a LCL filter is usually used in outlet of inverter (Liserre *et al*., 2006). In addition to mentioned items in reference (Kroutikova and Green, 2007), PI controlling method in synchrony framework is used to control power electronic interface of inverter sources. Simplicity of PI controller structure and its adequate performance to remove permanent fault for DC input signals has led to use this type of controller to control voltage and current of inverters in synchronic framework in which signals are type DC or similar to it (Rokrok and Golshan, 2009). Wang *et al*. (2005) proportional-resonant controller is analyzed to use power electronic interface control of inverter voltage sources. Komurcugi (2012), efficient controlling methods are used to track source signals in presence of uncertainties of system model using back-stepping method. Tan *et al*. (2006), coefficients of sliding mode are estimated by fuzzy logic algorithm and have led to increase in dynamic voltage stability level. Proposed controlling system is also designed based on back-stepping method and using sliding mode controllers in framework of qd synchrony.

MATERIALS AND METHODS

Structure of microgrid with presence of DG sources: Structure of studied power system includes permanent magnetic generator with back-to-back converters, solar module, boost converter and invertor as it is illustrated in Fig. 1.

The converter is embedded in order to extract maximum power of PMSG and to transmit the power to the grid. Battery charger is also embedded as support for islanded mode.

Sliding Mode Control (SMC) to extract maximum power of PMSG: As wind power generation system using PMSG has nonlinear property it is essential to choose a suitable controller. Although, PI controller has good function, it is not a good controller for robust control. Hence, the properties of its robustness in different wind speeds are not reliable. To solve this problem and to overcome this level of nonlinear property of system, it is required to use a nonlinear controller.

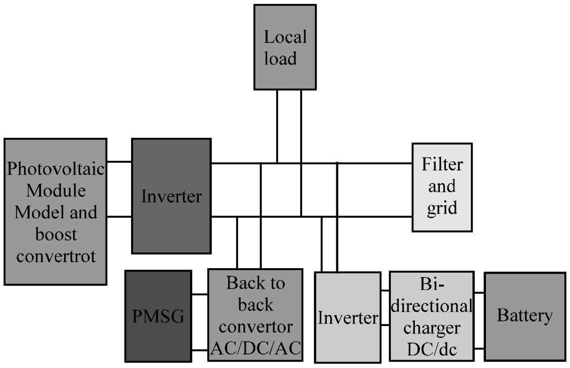

Fig. 1: Structure of studied power system

Among different available techniques, SMC is recognized as a perfectly adequate controller, since it is based on high speed feedback control and can be used easily in switching circuits such as extraction of wind energy. Another advantage of SMC is its robustness to external noises and changes in system parameters.

Sliding mode control is a feedback control which guarantees stability of nonlinear systems. The main idea of SMC is using discontinuous control input to put mode path of a nonlinear system to get it in certain zone. This zone is called sliding surface. The convergence of track state in SMC has two steps of reach and sliding steps (Wang, 2006).

Formulation of sliding mode control: In sliding mode control system, sliding is introduced as follows:

$$S = \dot{e} + e \tag{1}$$

Sliding is totalspeed error rate and derivative velocity error. In normal mode and according toLyapunov law for sustainability, output of SMC of first order should be as follows:

$$u = -K\,\mathrm{sgn}(S) \tag{2}$$

In Eq. 2, to achieve higher sustainability of controller, K value should be high. On the other hand, high value of K can make the controller apply more powerful strikes on system and create charting problem. Moreover, it can lead to lack of proper action of controlling system near to sliding line. To smooth these strikes, sometimes, Saturation (Sat) function is used which can't solve the mentioned problem absolutely. In this study, a SMC method is used with simple implementation. In the sync rotating frame using orthogonal signals, active and reactive equations could be presented as follows (Knight and Peters, 2005; Amei *et al*., 2002):

$$\begin{cases} P = \dfrac{1}{2}(V_\alpha i_\alpha + V_\beta i_\beta) \\ Q = \dfrac{1}{2}(V_\beta i_\alpha - V_\alpha i_\beta) \end{cases} \tag{3}$$

Where:

$g\alpha$ and $g\beta$ = Refer to current/voltage of components of
α and β = Axis in constant frame of $\alpha\beta$ as a result, the currents in axis α and β are calculated as follows

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{V_\alpha^2 + V_\beta^2}\begin{pmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{pmatrix}\begin{bmatrix} P \\ Q \end{bmatrix} \tag{4}$$

Instead of active and reactive power, error of powers with reference values could be used. As active and reactive powers are constant in steady state, PI controller could be used:

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{2}{V_\alpha^2 + V_\beta^2}\begin{pmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{pmatrix}\begin{bmatrix} G_p(S)(P - P^*) \\ G_q(S)(Q - Q^*) \end{bmatrix} \tag{5}$$

The sign * refers to reference values; $G_p(S)$ and G_q (S), respectively refer to proportional-integral controller:

$$\begin{aligned} G_p(S) &= k_{pp} + k_{pi}\frac{1}{s} \\ G_q(S) &= k_{pq} + k_{qi}\frac{1}{s} \end{aligned} \tag{6}$$

As it is obvious, active power is in proportion with DC link voltage. Hence, DC link voltage could be used instead of active power differences:

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{2}{V_\alpha^2 + V_\beta^2}\begin{pmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{pmatrix}\begin{bmatrix} G_p(S)(V_{dc} - V_{dc}^*) \\ (Q - Q^*) \end{bmatrix} \tag{7}$$

Then, $\alpha\beta0$ is changed into abc. Now, sliding level is defined as follows:

$$S(x, y) = i^*_{abc} - i_{abc} \tag{8}$$

Where:

$$\begin{aligned} S(x, y) > \varepsilon &\Rightarrow v_{pwm} = v_{dc} \\ S(x, y) < \varepsilon &\Rightarrow v_{pwm} = -v_{dc} \end{aligned} \tag{9}$$

Gp controlling coefficients are considered to 10 for proportional controller and to 100 for integral controller.

Analysis of solar system

Boost converter and its control: Boost circuit includes adiode, a switch and an inductor as it is illustrated in Fig. 2 hich is coupled to common DC bus and its inlet is PV. Output voltage of boost converter is stabilized through grid or battery (in islanded mode).

After determining amount of reference voltage by MPPT algorithm, it is compared to measured value and the obtained error level is sent to PI controller for compensation. Outlet of controller also generates switch pulse.

Applied inverter and its control: Similar to wind turbine, an inverter is used for DC/AC covert and connection to charge and AC grid. Inverter is 6-switch inverter with PWM control. Inverter control has two goals of stabilizing DC bus voltage and reactive power control similar to the grid side converter for wind turbine. Applied controlling block for inverter is illustrated in Fig. 3.

Battery and relevant circuits: Dc link voltage control is done using a bidirectional boost converter as it is illustrated in Fig. 4. It could be observed that link voltage is compared to 700 Volt and the result is sent to PI controller. An internal control loop is also embedded to improve controlling system performance which takes self-feedback from the current and compares it with PI output. Internal circuit of bidirectional boost converter is presented in Fig. 5 and in charging mode and transmission of power from bus to battery; converter is changed into dimming transformer. However, in discharging mode, bidirectional converter is changed into boost converter.

In outlet of battery, an inverter is needed to be coupled to the grid and its structure and controlling method in state of coupled to grid is similar to the inverter used for PV. However, in reverse mode, the battery is responsible for stabilizing charge voltage or same AC link. For this purpose, Vd voltage control method is used. In this method, after detecting islanded mode, d axis voltage is compared with its reference value that is same charge voltage peak. Q axis voltage has also reference value of 0. Figure 6 has shown controlling method of battery in islanded mode.

Simulation and the results: In this study, the studied system is simulated using MATLAB/SIMULINK Software and the obtained results are analyzed under different functional conditions. Using SMC method presented for dc link voltage control implemented as sample for wind system, the system has been resistant against changes of working points.

Studied system: Distributed Generation (DG) sources used in this study include an 8 kW solar array and a PMSG wind turbine with capacity of 8 kW and a battery. The purpose is to inject active power to the grid in output voltage of 220 V of AC. However, reactive power should be in its minimum level and while disconnection of the grid (is landing), local load should be supplied. Boost

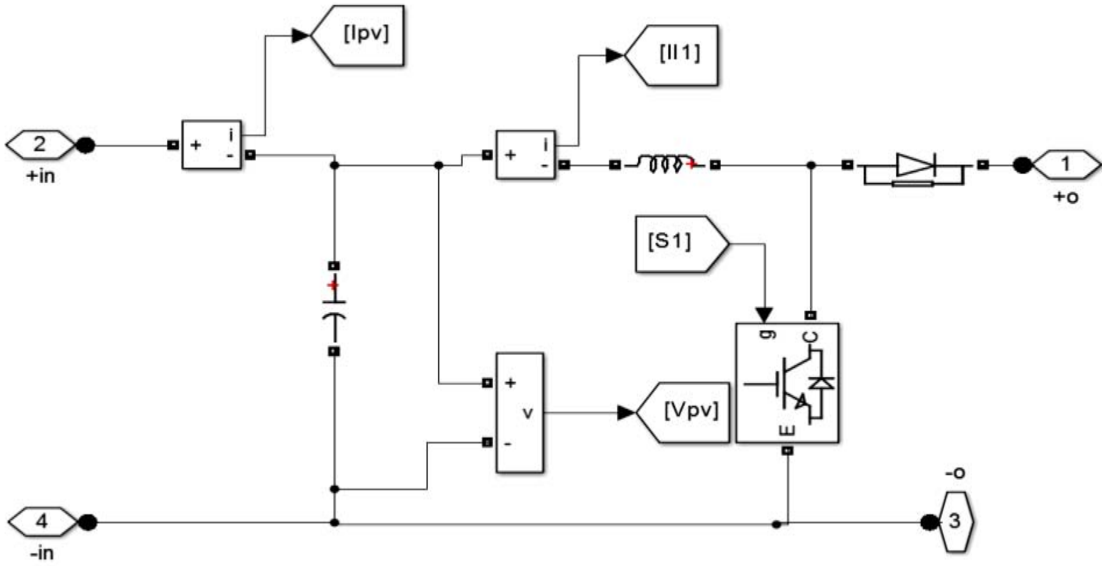

Fig. 2: The block related to boost converter

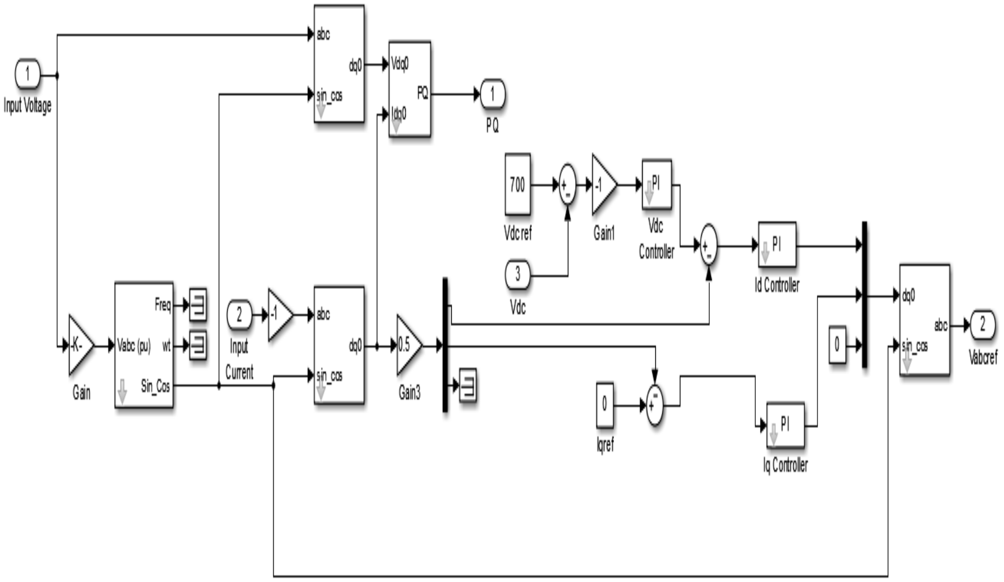

Fig. 3: Implementation of inverter control in solar system

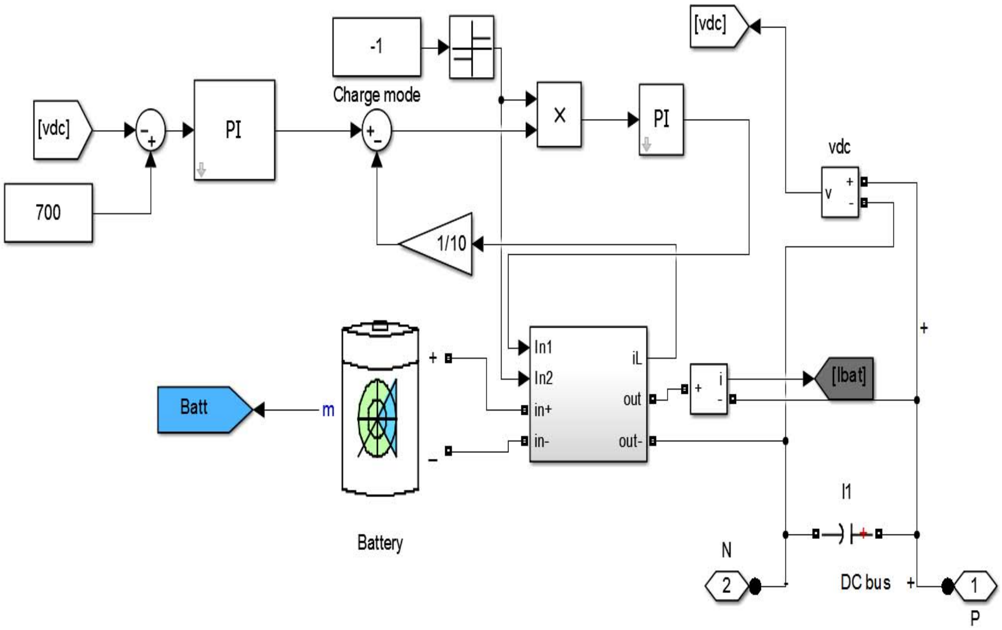

Fig. 4: Manner of dc bus control related to storage system

chopper switching frequency for solar converter is selected to 10 kHz and switching frequency of inverter is selected to 15 kHz. Size of capacitor of dc link is selected in such level that voltage ripple is below 1%:

$L1 = 2$ mH, $C1 = 220$ μF,
CDC BUS $= 2200$ μF, $L2 = 3$ mH

In battery, used bidirectional chopper switching frequency is equal to 10 kHz and the switching frequency of inverter is equal to 15 kHz. Size of capacitor is selected in such manner that voltage ripple is below 1%:

$L1 = 2$ mH, $C1 = 5000$ μF, CDC BUS $= 8000$ μF,
$L2 = 40$ mH, $L3 = 200$ mH

In block of wind turbine switching frequency of converter is equal to 2 kHz and switching frequency of inverter is equal to 2.7 kHz. Size of capacitor of dc link is selected to a level that voltage ripple is below 1%.

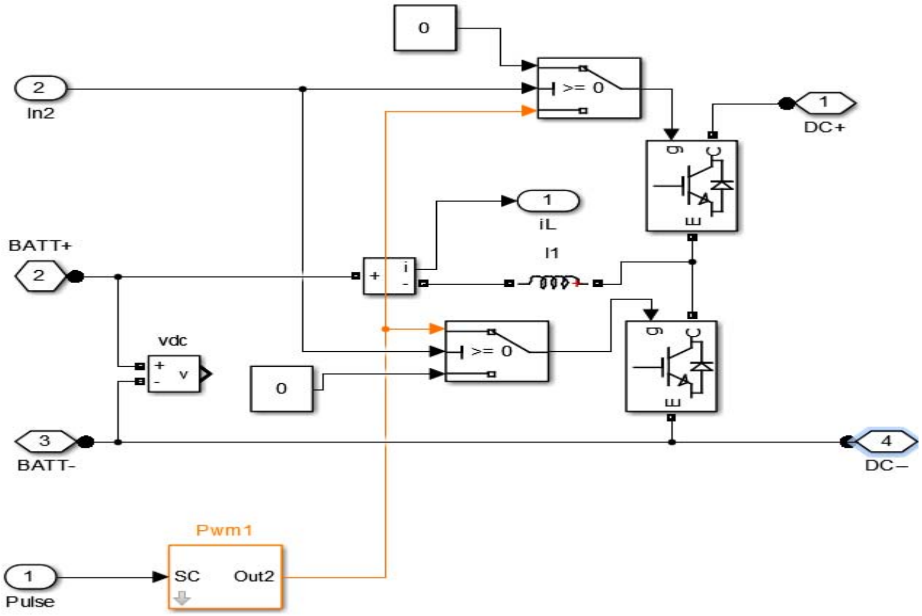

Fig. 5: Bidirectional boost converter for battery charge-discharge

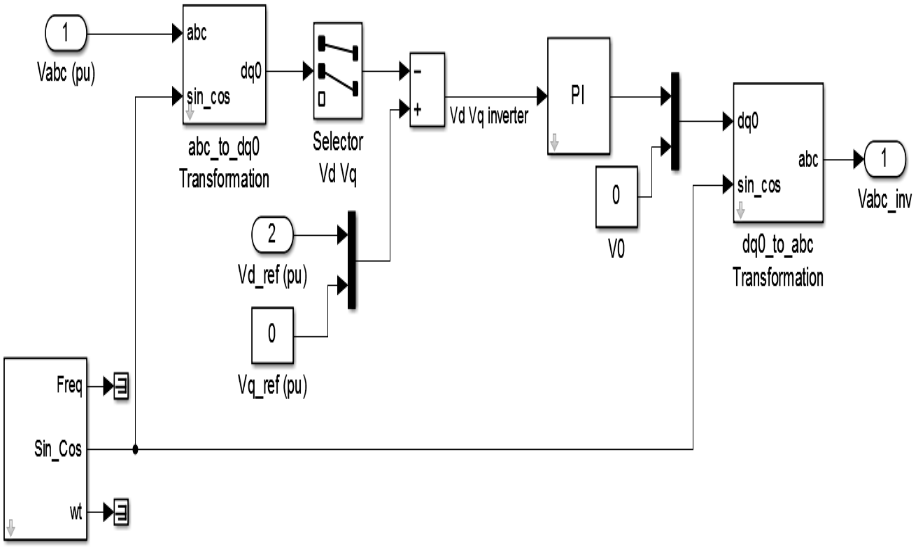

Fig. 6: Battery system control block in islanded mode

$$C_{DC\ BUS} = 10000\ \mu F$$

RESULTS AND DISCUSSION

Simulation results: In this section, in order to show accurate function of microgrid linked to three-phase 380 V and 60 Hz grid and 15 kW load, the system is simulated. Solar system includes 8 series arrays and 5 parallel arrays. Maximum current of each array in nominal radiation and temperature is equal to 7.61 Amp and maximum voltage is equal 26.3 V. In simulations, solar radiation is considered to 1000 Wm^2 and wind system is considered with velocity of 12 m sec^{-1} and battery system with 56 battery of 100 AH with initial charge of 40%.

Results of solar system: As it was mentioned, one of the controllers related to DC link voltage is MPPT. Reference value is considered to 700 V. Now, boost converter is responsible for regulating input voltage (PV). MPPT of modules occur in 210 V and hence, it can change boost

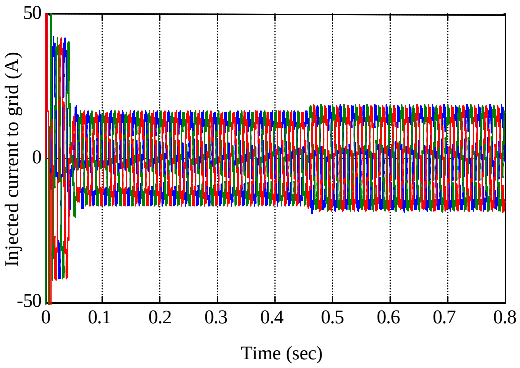

Fig. 7: Changes in solar system current injected to grid

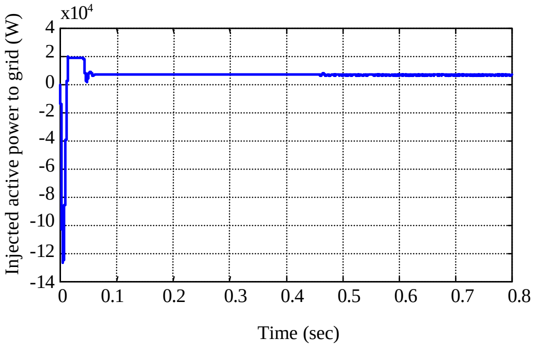

Fig. 8: Injected active power to grid by solar system

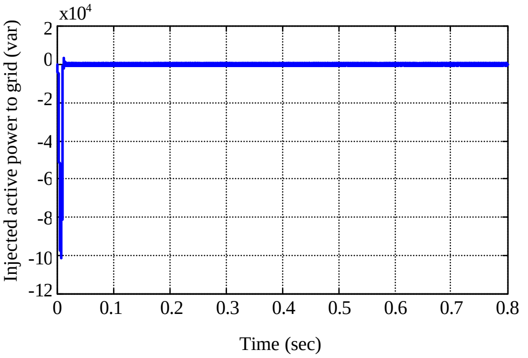

Fig. 9: Injected reactive power to grid by solar system

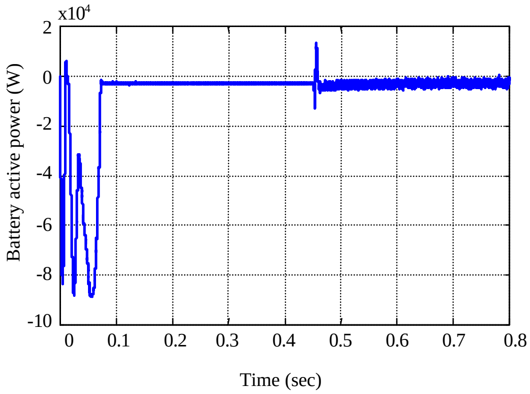

Fig. 10: Active power injected by storage system

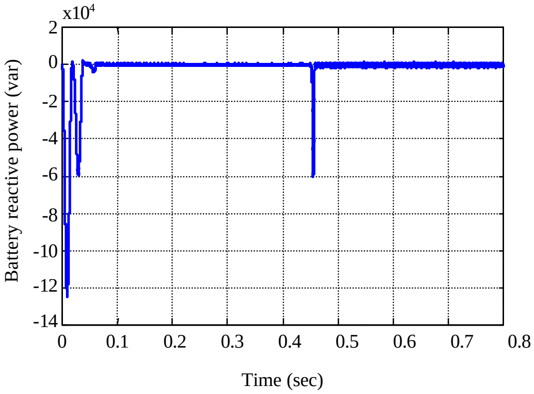

Fig. 11: Injected reactive power by storage system

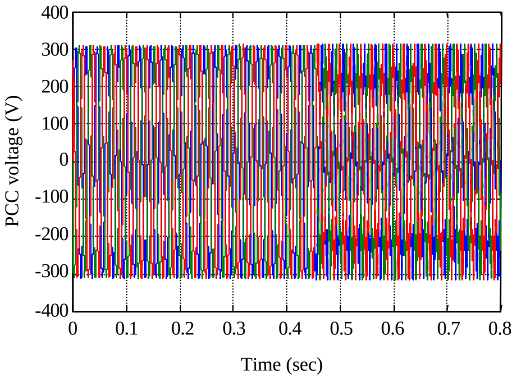

Fig. 12: Voltage changes before and after islanding system

converter 210-700. As working point of panels in in maximum level, their current would be also maximum current. The grid is modeled in form of infinite bus and grid voltage is in sinus form and has effective line-to-line voltage of 380 V. As solar array acts as a current source, changes of injected currents to the network are illustrated in Fig. 7. Moreover, injected active power to the grid by solar system is equal 8000 W as it is illustrated in Fig. 8. Reactive power source in q axis controller is also equal 0. Figure 9 shows injected reactive power to the grid which is regulated in level 0. Because of lack of transmission of reactive power, injected voltage and current to grid have same phase.

Results of output of storage system: As it was mentioned before, power is stored in battery in mode of coupled to grid and in islanded mode; the power is transmitted to current because of current supply. Figure 10-13 have

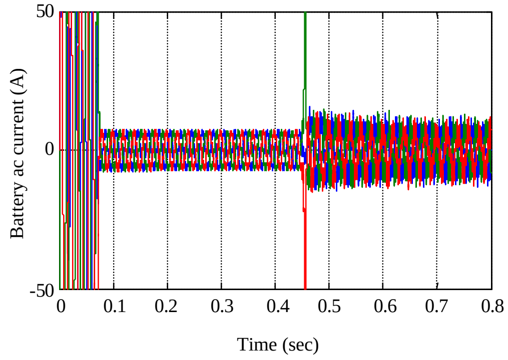

Fig. 13: Output current of battery before and after islanding system

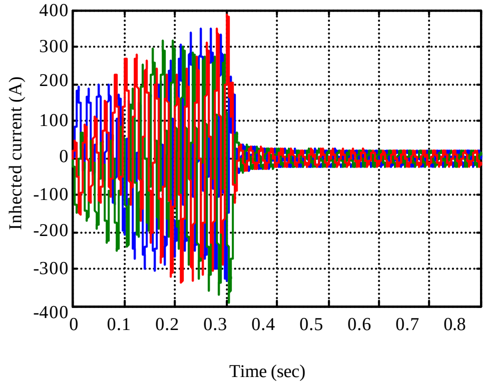

Fig. 15: Injected current to grid by wind system

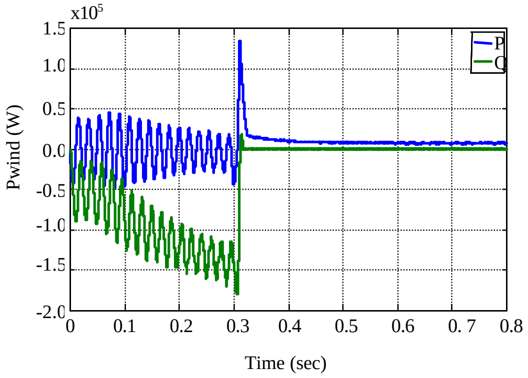

Fig. 14: Injected active and reactive power to grid by wind system

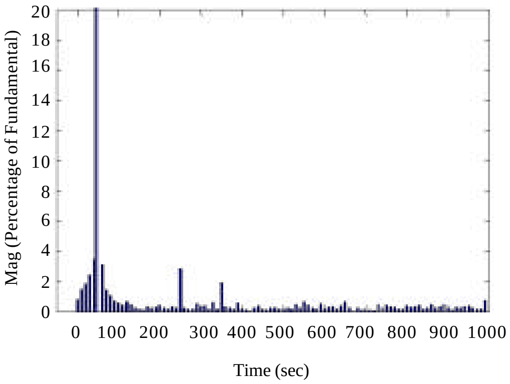

Fig. 16: Harmonic spectrum of injected current to grid in wind speed of 12 msec^{-1}

shown, respectively active and reactive power injected to battery. Moreover, changes in voltage and output current before and after islanding system.

As it was observed, current voltage is equal to grid voltage to the 0.45 sec that grid connection is available. However, when the grid is removed, current voltage is stabilized by battery and this can result in extraction of maximum power from other DG sources.

The results related to wind system: Till the 0.3 sec, wind turbine system controllers in sliding mode have no suitable reaction and have showed no function. Injected active power to the grid is equal 8000 W in wind speed of 12 m sec^{-1}. Figure 14 has illustrated active and reactive power injected to the grid. Usually, reactive power injection can occupy capacity of convertors and excepted for cases of needing reactive power injection, no injection is usually conducted.

Injected current to grid is shown in Fig. 15. In state that wind speed is equal to 12 m sec^{-1}, a current with range of 20.21 amp with total harmonic turbulences of 7.79% us injected to the grid and this is shown in Fig. 16. In terms of harmonic spectrum, it could be observed that third and fifth harmonies have maximum value compared to other harmonics.

CONCLUSION

The limitations related to fossil fuel have made people to take effort to reduce use of these resources and more use of renewable resources. The main strategies and solutions used in developed countries are using concept of Distributed Generation (DG). Increased presence of DG sources in power systems has introduced new structure called microgrid. In this study, evaluation of performance of wind and solar DG sources under normal and islanded modes is emphasized. The presented method in this study is based on observation and chaos approach in combination with Sliding Mode Control (SMC). Obtained results from the study showed that this controlling method can make system extract maximum power of DG sources and can provide required stability for system in islanded mode. SMC method used for adequate performance of wind system has made microgrid provide maximum possible power for the grid while islanding and has also enabled microgrid to supply loads even in case of being disconnected from the grid. In structure of microgrid studied here, in addition to wind system, storage system and solar system are also considered. Performance of each system was analyzed in islanded mode in this study and the obtained results showed that the method presented in this research can be suitable method to supply currents while islanded function of power grid.

REFERENCES

Amei, K., Y. Takayasu, T. Ohji and M. Sakui, 2002. A maximum power control of wind generator system using a permanent magnet synchronous generator and a boost chopper circuit. Proceedings of the Conference on Power Conversion PCC-Osaka, April 2-5, 2002, IEEE, Japan, ISBN:0-7803-7156-9, pp: 1447-1452.

Diaf, S., G. Notton, M. Belhamel, M. Haddadi and A. Louche, 2008. Design and techno-economical optimization for hybrid PV-wind system under various meteorological conditions. Appl. Energy, 85: 968-987.

Green, T.C. and M. Prodanovic, 2007. Control of inverter-based micro-grids. Electr. Power Syst. Res., 77: 1204-1213.

Hatziadoniu, C.J., E.N. Nikolov and F. Pourboghrat, 2003. Power conditioner control and protection for distributed generators and storage. IEEE. Trans. Power Syst., 18: 83-90.

Ito, Y. and S. Kawauchi, 1995. Microprocessor based robust digital control for UPS with three-phase PWM inverter. IEEE. Trans. Power Electron., 10: 196-204.

Katiraei, F., M.R. Iravani and P.W. Lehn, 2005. Micro-grid autonomous operation during and subsequent to islanding process. IEEE. Trans. Power Delivery, 20: 248-257.

Knight, A.M. and G.E. Peters, 2005. Simple wind energy controller for an expanded operating range. IEEE Trans. Energy Conver., 20: 459-466.

Komurcugil, H., 2012. Rotating-sliding-line-based sliding-mode control for single-phase UPS inverters. IEEE. Trans. Ind. Electron., 59: 3719-3726.

Kroutikova, N. and T.C. Green, 2007. State-space model of grid-connected inverters under current control mode. IET. Electric Power Appl., 1: 329-338.

Kukrer, O., 1996. Deadbeat control of a three-phase inverter with an output LC filter. IEEE. Trans. Power Electron., 11: 16-23.

Lasseter, R., A. Akhil, C. Marnay, J. Stephens and J. Dagle *et al*., 2002. Consortium for electric reliability technology solutions. MSc Thesis, Department of Energy, University of California, USA. https://pdfs.semanticscholar.org/af2d/a724eeef8485f767ecd0ec140e14bed0964f.pdf

Lasseter, R.H., 2002. Microgrids. Proceedings of the IEEE Conference on Power Engineering Society Winter Meeting, January 27-31, 2002, IEEE, New York, USA., ISBN:0-7803-7322-7, pp: 305-308.

Liserre, M., R. Teodorescu and F. Blaabjerg, 2006. Stability of photovoltaic and wind turbine grid-connected inverters for a large set of grid impedance values. IEEE Trans. Power Electron., 21: 263-272.

Majumder, R., A. Ghosh, G. Ledwich and F. Zare, 2009. Load sharing and power quality enhanced operation of a distributed microgrid. IET. Renewable Power Generation, 3: 109-119.

Marei, M.I., E.F. El-Saadany and M.M.A. Salama, 2004. A novel control algorithm for the DG interface to mitigate power quality problems. IEEE Trans. Power Delivery, 19: 1384-1392.

Marwali, M.N. and A. Keyhani, 2004. Control of distributed generation systems-Part I: Voltages and currents control. IEEE Trans. Power Electron., 19: 1541-1550.

Rokrok, E. and M.H. Golshan, 2009. Comprehensive control scheme for an inverter-based distributed generation unit. Iran. J. Sci. Technol., 33: 477-490.

Salam, A.A., A. Mohamed and M.A. Hannan, 2008. Technical challenges on microgrids. ARPN J. Eng. Applied Sci., 3: 64-69.

Tan, S.C., Y.M. Lai, C.K. Tse and M.K.H. Cheung, 2006. Adaptive feedforward and feedback control schemes for sliding mode controlled power converters. IEEE Trans. Power Electr., 21: 182-192.

Wang, B.H., C.W. Yang and Q. Zhang, 2005. Design of adaptive backstepping controller for TCSC. Electric Power Autom. Equip., 25: 59-61.

Wang, C., 2006. Modeling and control of hybrid wind-photovoltaic-fuel cell distributed generation systems. Ph.D Thesis, Montana State University, Bozeman, Montana.