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OPTIMAL DESIGN OF MICROGRID IN AN AUTONOMOUS MODE USING ANT COLONY OPTIMIZATION

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Abstract - The dynamic nature of the distribution network challenges the stability and control effectiveness of the microgrid in autonomous mode. In this paper, nonlinear model of microgrid operating in autonomous mode has been presented. The controller parameters and power sharing coefficients are optimized in case of autonomous mode. The control problem has been formulated as an optimization problem where Ant colony optimization is employed to search for optimal settings of the optimized parameters. In addition, nonlinear time-domain-based objective function has been proposed to minimize the error in the measured power and to enhance the damping characteristics, respectively. Finally, the nonlinear time-domain simulation has been carried out to assess the effectiveness of the proposed controllers under different disturbances and loading conditions. The results show satisfactory performance with efficient damping characteristics of the microgrid considered in this study.

Keywords- *Autonomous mode, controller design and inverter control, distributed generator (DG), droop-control concepts, inverter-based distributed generators, microgrid stability, optimal control, optimal power sharing, Ant colony optimization (ACO), power electronic inverters.*

I. INTRODUCTION

Recent innovations in small-scale distributed power generation systems combined with technological advancements in power electronic systems led to concepts of future network technologies such as microgrid. These small autonomous regions of power systems can offer increased reliability and efficiency and can help integrate renewable energy and other forms of distributed generation (DG) [1]. Many forms of distributed generation such as fuel-cells, photovoltaic and micro-turbines are interfaced to the network through power electronic converters [2]–[5]. These interface devices make the sources more flexible in their operation and control compared to the conventional electrical machines. However, due to their negligible physical inertia they also make the system potentially susceptible to oscillation resulting from network disturbances.

A microgrid can be operated either in grid connected mode or in stand-alone mode. In grid connected mode, most of the system-level dynamics are dictated by the main grid due to the relatively small size of micro sources. In stand-alone mode, the system dynamics are dictated by micro sources themselves, their power regulation control and, to an unusual degree, by the network itself.

In this paper, a systematic approach to modeling an inverter-based microgrid is presented. Each DG inverter will have an outer power loop based on droop control to share the-fundamental real and reactive powers with other DGs. Inverter internal controls will include voltage and current controllers which are designed to reject high frequency disturbances and damp the output filter to avoid any

resonance with the external network. The small-signal state-space model of an individual inverter is constructed by including the controllers, output filter and coupling inductor on a synchronous reference frame whose rotation frequency is set by the power controller of that inverter. An arbitrary choice is made to select one inverter frame as the common reference frame and all other inverters are translated to this common reference frame using the simple transformation techniques familiar in synchronous machine systems. It is considered that state-less impedance models of the network are inadequate for use with full-order inverter models which include high frequency modes. Instead a dynamic (state-space) model of the network is formed on the common reference frame.

Recently, computational intelligence algorithms such as genetic algorithm (GA) and ant colony optimization (ACO) have been applied to different power system problems with impressive success [6]. However, some deficiencies in GA performance such as the premature convergence have been recorded. On the other hand, ACO has been widely implemented and stamped as one of the promising optimization technique due to its simplicity, computational efficiency, and robustness.

In this paper, a single code for modeling, optimization, linearization, and nonlinear time-domain simulation has been developed. A new technique for stability enhancement of a microgrid operating in autonomous mode is proposed in this paper. Voltage source inverter (VSI), LC filter, coupling inductance, phase-locked loop (PLL), lines, loads, and power, current, and voltage controllers have been modeled. The design problem of different microgrid components and controllers' parameters

has been formulated as an optimization problem where ACO is employed to solve this design problem. The nonlinear time-domain simulation-based objective functions are considered with the aim of autonomous microgrid stability enhancement where the controller parameters and the power sharing coefficients are optimized. The performance of the microgrid with the proposed controllers and optimal settings under different disturbances has been examined through the nonlinear time-domain simulations. The results show the effectiveness of the proposed approach to enhance the stability of the microgrid considered.

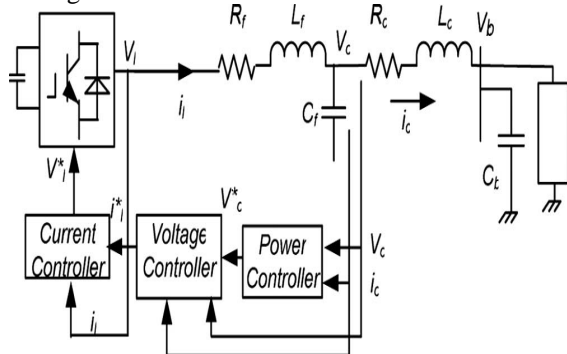


Fig. 1 : Microgrid in autonomous mode.

II. MICROGRID MODELING IN AUTONOMOUS MODE

This section provides the mathematical model of the autonomous microgrid consisting of VSI controller connected to the loads through LC filter and coupling inductance.

A. Modeling of VSI and Its controllers

Power, current, and voltage controllers have been used to control the microgrid inverter in the autonomous mode, as shown in Fig. 1. First, the active and reactive powers are calculated using the measured output current and voltage of the VSI. An external power control loop sets the magnitude and frequency (and hence, phase) for the fundamental component of the inverter output voltage according to the droop characteristics set for the real and reactive powers [7]. Then, the voltage and current controllers are designed to reject high-frequency disturbances and provide sufficient damping for the LC filter [9].

B. Power Controller

In a conventional power system, synchronous generators share any increase in the load by decreasing the frequency according to their governor droop characteristic. In the autonomous mode, the inverter emulates the behavior of a synchronous machine. Therefore, the angle δ can be controlled by regulating P , while the output voltage is controllable through Q . Control of frequency dynamically controls the power angle,

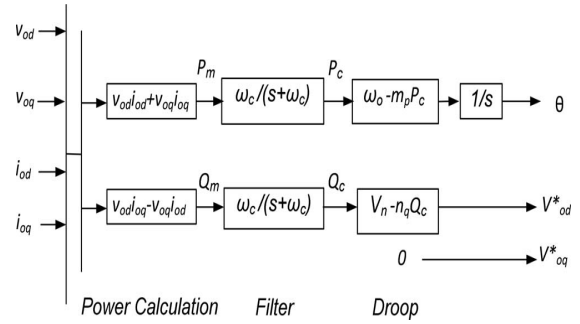


Fig. 2 : Block diagram of power controller.

and thus, the real power flow [9]. For stable operation, the real and reactive power output of the inverters should be properly controlled. First, the measured output voltage and current are used to calculate the instantaneous active and reactive power $\tilde{p} = v_{od}i_{od} + v_{oq}i_{oq}$, $\tilde{q} = v_{od}i_{oq} - v_{oq}i_{od}$

Second, the real and reactive powers, P_c and Q_c , corresponding to the fundamental components are obtained after passing these powers through low-pass filter. Finally, the frequency ω and the output d-axis voltage magnitude reference can be determined as

$$\omega = \omega_n - m_p P_c, \theta \dot{=} \omega$$

$$v_{od}^* = v_n - n_q Q_c, v_{oq}^* = 0$$

Where and are the real and reactive power sharing coefficients. The different droop characteristics show that the three inverters can share the total real and reactive power.

C. Voltage Controller

The voltage controller block diagram including all feed-back and feed-forward terms. Output voltage control is achieved with a standard PI controller.

Along with the algebraic equations

$$\dot{Q}_d = v_{od}^* - v_{od} Q_q = v_{oq}^* - v_{oq} Q_q$$

Along with the algebraic equations

$$i_{id}^* = F_{i_{od}} - \omega_n C_f v_{oq} + k_{pv} (v_{od}^* - v_{od}) + k_{iv} Q_d$$

$$i_{iq}^* = F_{i_{oq}} - \omega_n C_f v_{od} + k_{pv} (v_{oq}^* - v_{oq}) + k_{iv} Q_q$$

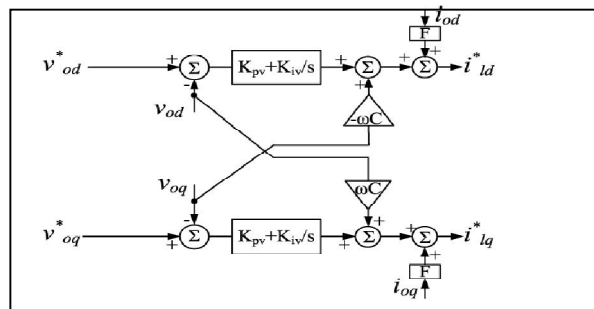


Fig. 3 : Voltage controller in autonomous mode.

D. Current Controller

The PI current controller structure is shown in Fig. The corresponding state-space model is

$$\begin{aligned} \dot{y}_d &= i_{id}^* - i_{id}, \dot{y}_q = i_{iq}^* - i_{iq} \\ v_{id}^* &= -\omega_n L_f i_{iq} + k_{pc}(i_{id}^* - i_{id}) \\ &\quad + k_{ic} y_d \\ v_{iq}^* &= \omega_n L_f i_{id} + k_{pc}(i_{iq}^* - i_{iq}) \\ &\quad + k_{ic} y_q \end{aligned} \quad (8)$$

Where k_{pc} and k_{ic} are the PI current controller parameters.

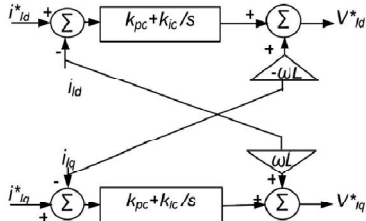


Fig. 4 : Current controller in autonomous mode.

E. LC Filter and Coupling Inductance

The LC filter and the coupling inductance model can be described with the following state equations, assuming that inverter produces the demanded voltage

$$\begin{aligned} \dot{i}_{id} &= -\frac{R_f}{L_f} i_{id} + \omega i_{iq} \\ &\quad + \frac{1}{L_f} (v_{id} - v_{od}) \\ \dot{i}_{iq} &= -\frac{R_f}{L_f} i_{iq} + \omega i_{id} \\ &\quad + \frac{1}{L_f} (v_{iq} - v_{oq}) \end{aligned} \quad (9)$$

$$\begin{aligned} \dot{v}_{od} &= \omega v_{oq} + \frac{1}{C_f} (i_{id} - i_{od}), \quad \dot{v}_{oq} = \omega v_{od} + \\ &\quad \frac{1}{C_f} (i_{iq} - i_{oq}) \end{aligned} \quad (10)$$

$$\begin{aligned} \dot{i}_{od} &= -\frac{R_c}{L_c} i_{od} + \omega i_{oq} + \frac{1}{L_c} (v_{od} - v_{bd}) \\ \dot{i}_{oq} &= -\frac{R_c}{L_c} i_{oq} - \omega i_{od} \\ &\quad + \frac{1}{L_c} (v_{oq} - v_{bq}) \end{aligned} \quad (11)$$

F. Complete Inverter Model:

To build the whole model of the system, the output variables of each inverter should be converted to the common reference frame using the following transformation:

$$\begin{aligned} f_{DQ} &= T_i f_{dq} \\ T_i &= \begin{bmatrix} \cos(\delta_i) & -\sin(\delta_i) \\ \sin(\delta_i) & \cos(\delta_i) \end{bmatrix} \end{aligned} \quad (13)$$

The bus voltage that is the input signal to the inverter model should also be expressed on the

common reference frame using reverse transformation.

G. Line Model:

The state equations of line current of i th line connected between nodes j and k can be expressed on a common reference frame as follows:

$$\dot{i}_{lineDi} = -\frac{r_{linei}}{L_{linei}} i_{lineDi} + \omega i_{lineQi} + \frac{1}{L_{linei}} (v_{bDj} - v_{bDk}) \quad (14)$$

$$\begin{aligned} \dot{i}_{lineQi} &= -\frac{r_{linei}}{L_{linei}} i_{lineQi} + \omega i_{lineDi} \\ &\quad + \frac{1}{L_{linei}} (v_{bQj} - v_{bQk}) \end{aligned} \quad (15) \text{ Load Model:}$$

The state equations of the RL load connected at i th node are given as follows

$$\begin{aligned} \dot{i}_{lineDi} &= -\frac{R_{linei}}{L_{linei}} i_{lineDi} + \omega i_{lineQi} + \frac{1}{L_{linei}} (v_{bDi} - v_{bDi}) \\ \dot{i}_{lineQi} &= -\frac{R_{linei}}{L_{linei}} i_{lineQi} + \omega i_{lineDi} + \frac{1}{L_{linei}} (v_{bQi} - v_{bQi}) \end{aligned}$$

The load voltages are also given as follows:

$$\dot{v}_{bDi} = \omega v_{bQi} - \frac{1}{C_f} (i_{oDi} - i_{loadDi} \pm i_{lineDi,j}) \quad (18)$$

$$\dot{v}_{bQi} = -\omega v_{bDi} - \frac{1}{C_f} (i_{oQi} - i_{loadQi} \pm i_{lineQi,j}) \quad (19)$$

The sign in above equations depends on the current direction in the line.

III. ANT COLONY OPTIMIZATION

Ant Colony Optimization (ACO) is a population-based stochastic optimization technique developed by Dorigo & Stutzle [11] in 2004. ACO is a metaheuristic inspired by the foraging behavior of ant colonies. By marking the paths they have followed with pheromone trails, ants are able to communicate indirectly and find the shortest distance between their nest and a food source when foraging for food. When adapting this search metaphor of ants to solve discrete combinatorial optimization problems, artificial ants are considered to explore the search space of all possible solutions. The ACO search begins with a random solution (possibly biased by heuristic information) within the decision space of the problem. As the search progresses over discrete time intervals, ants deposit pheromone on the components of promising solutions[12]. In this way, the environment of a decision space is iteratively modified and the ACO search is gradually biased towards more desirable regions of the search space, where optimal or near-optimal solutions can be found. Due to its robustness in solving these problems, ACO has recently been applied to, and obtained some encouraging results for, real world

engineering problems, such as the design of optimal water distribution systems.

As is the case with other metaheuristics, ACO can be linked with existing simulation models of power system, regardless of their complexity, when solving a power sharing problem. In addition, the unique way in which ACO problems are represented by using an equation makes ACO inherently suitable for handling power sharing and stability problems. In this section, the novel formulation that enables ACO to be applied to power sharing problems.

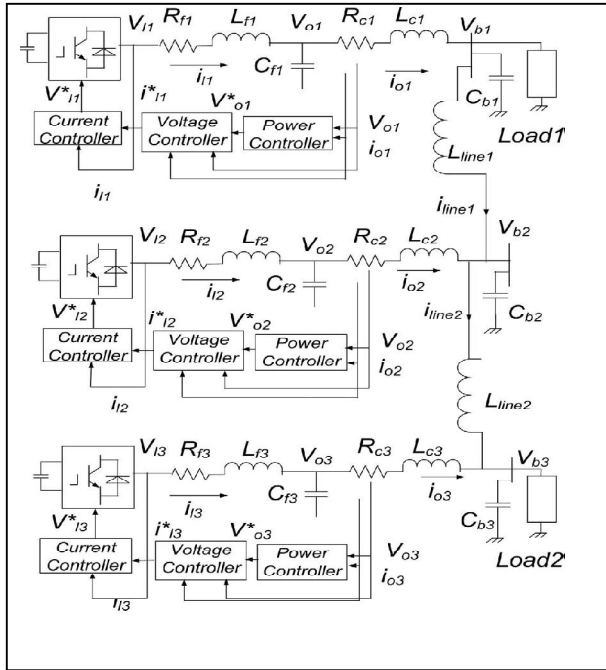


Fig. 5 : Circuit diagram of three inverter-based microgrid

IV. RESULTS AND DISCUSSION

Nonlinear model were developed using a MATLAB code to study the stability of an inverter-based microgrid when it is working in autonomous mode.

A. Autonomous Mode

In the autonomous mode, three inverter-based DGs (10 kVA) are connected with two loads through series LC filter, coupling inductance L_c , and lines as shown in Fig. 5. Each DG unit is represented by dc voltage source and VSI. A resistive load of 5.8 kW (25 Ω per phase) at load 1 and 7.3 kW (20 Ω per phase) at load 2 are considered as an initial operating point. The inverters are controlled to share the real and reactive powers over the lines. First, initial steady-state conditions of the system are obtained using a general power flow program. Second, nonlinear time-domain simulations have been carried out at two different disturbances to examine the effectiveness of the optimal settings of the proposed controllers and power sharing coefficients. The first one is a step change in real power and the second is a fault disturbance at load 1. The results are given as follows. Figs.7 show the system response under fault

disturbance at load 1. It can be seen that the system has satisfactory damping characteristics. Step change of 3.8 kW real power has also been applied. Figs. 6 show the system's response under this disturbance. Fig. 29 depicts the output voltage response of all the three inverters for a step load change.

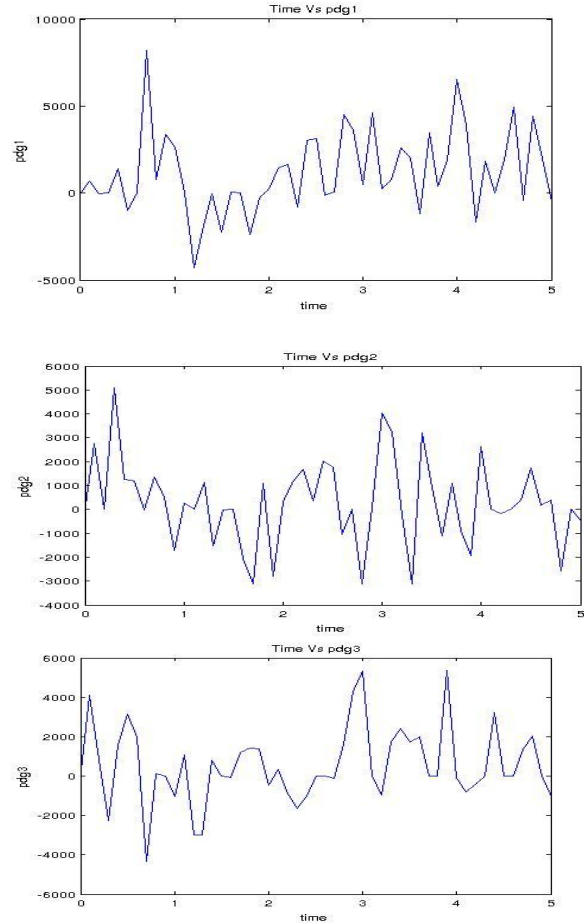
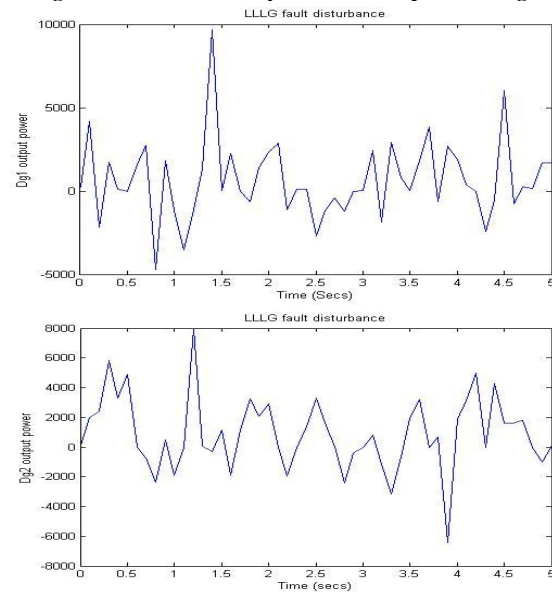


Fig. 6 : Behaviour of the system under step load change



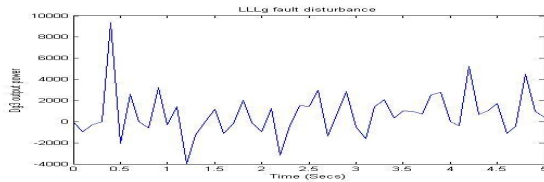


Fig. 7 : Behaviour of the system under fault disturbance at load 1

V. CONCLUSION

In this paper, nonlinear model of a microgrid operating in autonomous mode have been presented. The design of different controllers, filter, and power sharing coefficients has been formulated as an optimization problem. ACO technique is employed to search for the optimal settings of the optimized parameters. Different disturbances have been applied to demonstrate the effectiveness of the proposed design approach. System stability has been analyzed using nonlinear time-domain simulations. In an autonomous mode, step change and fault disturbances have been used to verify the system stability. The results confirm the effectiveness of the proposed ACO-based approach for optimizing the parameters of PI controllers, filter, and power sharing coefficients that achieve the satisfactory system performance under different disturbances.

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