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Fuzzy Based Control Technique for Integration of DG Units to the Grid

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ABSTRACT

This paper deals with a new control technique for integration of distributed generation (DG) resources to the electrical power network. The proposed strategy provides compensation for active, reactive, and harmonic load current components during connection of DG link to the grid. By setting an appropriate compensation current references from the sensed load currents in control circuit loop of DG, the active, reactive, and harmonic load current components will be compensated with fast dynamic response, thereby achieving sinusoidal grid currents in phase with load voltages, while required power of the load is more than the maximum injected power of the DG to the grid. In addition, the proposed control method of this paper does not need a phase-locked loop in control circuit and has fast dynamic response in providing active and reactive power components of the grid-connected loads. The effectiveness of the proposed control technique in DG application is demonstrated with injection of maximum available power from the DG to the grid, increased power factor of the utility grid, and reduced total harmonic distortion of grid current through simulation results under steady-state and dynamic operating conditions.

KEYWORDS: *Distributed generation (DG), renewable energy sources, total harmonic distortion (THD), voltage source converter (VSC).*

I. INTRODUCTION

Distributed generation (DG) technology also known as dispersed generation technology is electricity generating plant connected to a distribution grid rather than the transmission network. There are many types and sizes of DG facilities. These include wind farms, solar photovoltaic (PV) systems, hydroelectric power, or one of the new smaller generation technologies. The DG concept emerged as a way to integrate different power plants, increasing the DG owner's reliability and security, providing additional power quality benefits of the power grid [1], [2], and improving the air quality as a result of lower greenhouse gas emissions of air pollutants [3], [4]. In addition, the cost of the distribution power generation system using the renewable energies is on a falling trend and is expected to fall further as demand and production increase [5]. DG technology can come from conventional technologies such as motors powered by natural gas or diesel fuel or from renewable energy technologies, such as solar PV cells and wind farms.

Over the past two decades, declines in the costs of small scale electricity generation, increases in the reliability needs of many customers, and the partial deregulation of electricity markets have made DG technology more attractive to businesses and households as a supplement to utility-supplied
Power [6]. However, the increasing number of DG units in electrical networks requires new techniques for the operation and management of the power networks in order to maintain or even to improve the power supply reliability and quality in the future. As a consequence, the control of DG unit should be improved to meet the requirements for the electrical network.

Therefore, design of a control technique, which considers different situations of the electrical networks, becomes of high interest for interconnection of DG units to the power grid. Numerous control techniques and strategies have been proposed and reported for the control and connection of DG units to the electrical grid [7]. In [8], an overview of different control and synchronization techniques for DG systems has been presented. Different hardware structures for the DG system [9], control strategies for the grid-side converter, and control strategies under fault conditions were addressed [10], [11]. Different implementation techniques like dq, stationary, and natural frame control structures were presented, and their major characteristics were pointed out [12]. A discussion about different controllers in DG system and their ability to compensate low-order harmonic components presented in the utility grid was given [13]. Finally, an overview of grid synchronization strategies, their influences, and roles in the control of DG system on normal and faulty grid conditions were discussed [14]. In [15], a control concept was proposed that provides sharing of harmonic load currents between parallel connected converters without mutual communication. In this paper, a converter operates as an active inductor at a certain frequency to absorb the harmonic current components.

The impact of DG technology on distribution feeder reconfiguration was described in this paper; the cost summation of electrical power generated by DG technology and from substation buses was analyzed.

II. Proposed DG Model

Fig. 1 shows the schematic diagram of the proposed system.

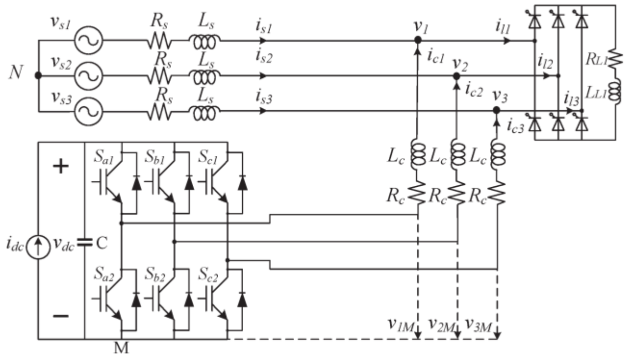

Fig. 1. Schematic diagram of the proposed DG system.

Conventional signs of voltages and currents components are also indicated in this schema, where R_c and L_c represent the equivalent resistance and inductance of the ac filter, coupling transformer, and connection cables; Rs and Ls represent the grid resistance and inductance up to the point of common coupling (PCC), respectively; v_k (k = 1, 2, 3) is the supply voltage components at the PCC; v_{sk} is the grid voltage components; v_{dc} is the dc-link voltage; and i_{sk}, i_{lk}, and i_{ck} are grid, load, and DG current components, respectively. In addition, the DG resources and additional components are represented as a dc current source which is connected to the dc side of the converter.

III. Modeling of the Proposed DG System

For the purposes of this paper, the electric power grid is composed of the generation system, the transmission, or the distribution system, and the loads. The DG source and additional components are represented as a dc current source connected to the dc side of the proposed converter. To draw an appropriate plan to control the integration of DG resources to the power grid, a dynamic analytical model of the proposed power system should be developed.

A. Proposed Model Analysis

Kirchhoff's laws of voltage and current applied to the proposed model shown in Fig. 1 provide a general equation in the stationary reference frame in a three-phase system as

$$\sum_{i=1}^{3} v_{iM} = \sum_{i=1}^{3} \left(L_c \frac{di_{ci}}{dt} + R_c i_{ci} + v_i + v_{NM} \right)$$

A null value for the zero voltage component is assumed. Since the absence of neutral wire is considered, the zero current component is also null, with the assumption that the grid voltages are balanced. By taking into account these assumptions, the ac neutral point voltage term can be obtained as

$$v_{NM} = \frac{(v_{1M} + v_{2M} + v_{3M})}{3} = \frac{1}{3}\sum_{i=1}^{3} v_{iM}$$

The switching function s_k of the k_{th} leg of the VSC can be expressed as

$$S_k = \begin{cases} 1, & \text{if } T_k \text{ is on and } T_k' \text{ is off} \\ 0, & \text{if } T_k \text{ is off and } T_k' \text{ is on.} \end{cases}$$

Thus, with $v_{kM} = S_k v_{dc}$ a set of dynamic equations describing the switched model of the proposed DG model is developed. This model is general, complete, and makes no assumptions other than the use of ideal Switches.

Equation represents phase k dynamic equation of the proposed VSC. By the switching state function can be

$$D_{nk} = \left(S_k - \frac{1}{3}\sum_{j=1}^{3} S_j\right)$$

Equation shows that the value of D_{nk} depends on the switching state n and on the phase k. In other words, D_{nk} depends simultaneously on the switching functions of the three legs of the interfaced VSC. This shows the interaction between
the three phases. The proposed model can be expressed as

$$\frac{d}{dt}\begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix} = -\frac{R_c}{L_c}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix} + \frac{1}{L_c}\begin{bmatrix} D_{n1} \\ D_{n2} \\ D_{n3} \end{bmatrix} v_{dc} - \frac{1}{L_c}\begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$$

To design PI regulator in circuit of current controller, it is necessary to decouple the model of the system by adding the measured voltage of d-axis and cross coupling terms as shown in Fig. 3, where L∗ and v∗ are estimated values of coupling inductance and grid voltages.

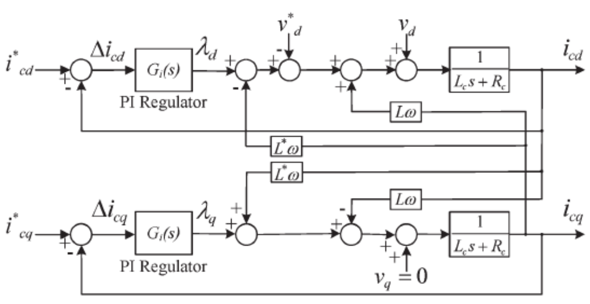

Fig. 3 inner control loop of the i_{cd} and i_{cq}

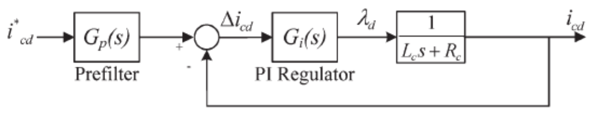

Fig.4 equivalent diagram of d-axis current control loop

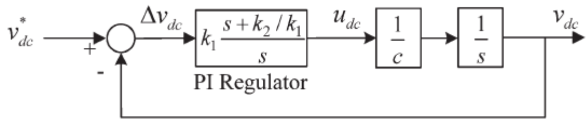

Fig.5 current control loop of dc voltage

The transient response of the currents will be affected by the presence of the zero. In particular, the actual percent overshoot will be much higher than expected. For the optimal value of the damping factor ζ =□ 1/2, the theoretical overshoot is 20.79%. To eliminate the effect of zero on transient response, a pre filter is added as shown in Fig. 4. The response of the current loops becomes that of a second-order transfer function with no zero. Comparison between general model of a second-order transfer function leads to the following design relations:

$$k_p = 2L_c\zeta\omega_n - R_c \qquad k_i = L_c \cdot \omega_n^2$$

Where ωn is natural undamped angular frequency and depends on the specific time response.

IV. Simulation Analysis and Results

In order to demonstrate the high performance of the proposed control technique, the complete system model was simulated using the "Power System Block set" simulator operating under the Matlab/Simulink environment. The schematic diagram and principle of the proposed model and the control technique in an ac grid are shown in Fig. 6.

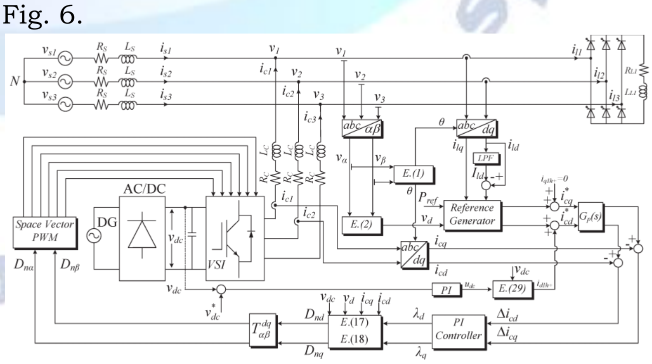

Fig.6 General Schematic diagram of the proposed control strategy for DG system

At first, capabilities of DG resources and flexibility of proposed control strategy to control the proposed VSC in providing active, reactive, and harmonic current components of different loads are shown, and the capabilities of proposed control method on reactive power tracking with constant output active power are considered. In addition, the simulated results have been used to analyze the total harmonic distortion (THD) of the utility grid current amid severe varying load conditions. During the simulation process, constant dc voltage sources have been considered as a DG source. In addition, the active power which is delivered from the DG link to the ac grid is considered to be constant. This assumption makes it possible to evaluate the capability of the proposed control strategy to track the fast change in the active and reactive power, independent of each other. For this purpose, when one of them is changed, another one must be constant. To simulate a real ac grid, the load is connected and disconnected to the power grid randomly, and grid current waveform will be compared with each other under various loads and conditions.

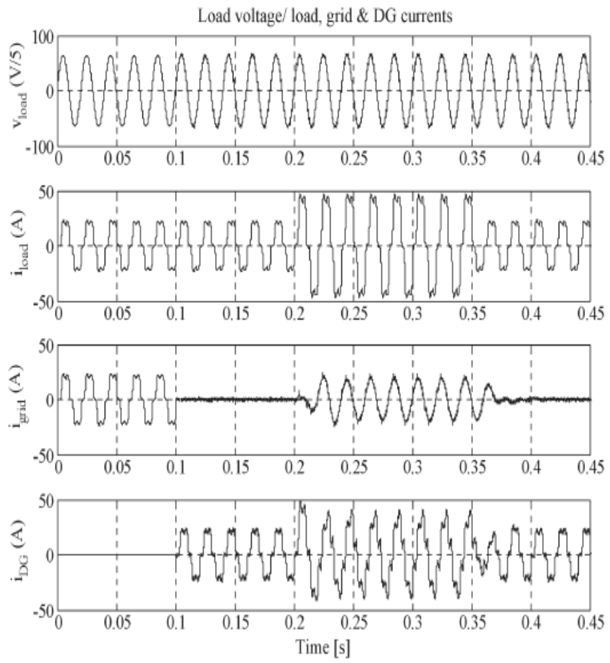

Fig. 7. Load voltage, load, grid, and DG currents before and after connection of DG and before and after connection and disconnection of additional load into the grid.

Load voltage, load, grid, and DG currents before and after connection of DG and before and after connection and disconnection of additional load into the grid. This nonlinear load draws harmonic currents from the grid continuously. The DG link is Connected to the ac grid at $t = 0.1$ s. This process is continued until $t = 0.2$; at this moment, another full-wave thyristor converter similar to the prior load is connected to the grid, and it is disconnected from the grid at $t = 0.35$ s.

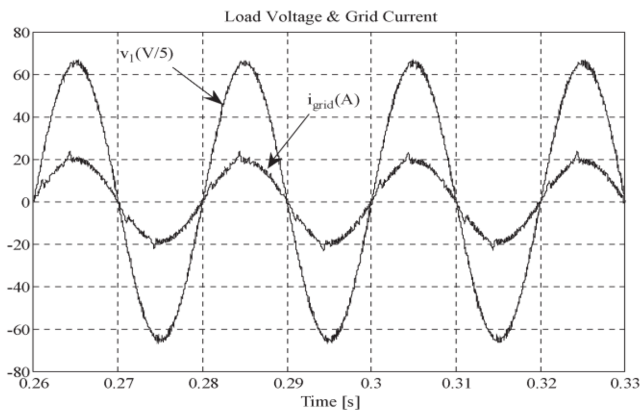

Fig. 8. Phase-to-neutral voltage and grid current for phase (a).

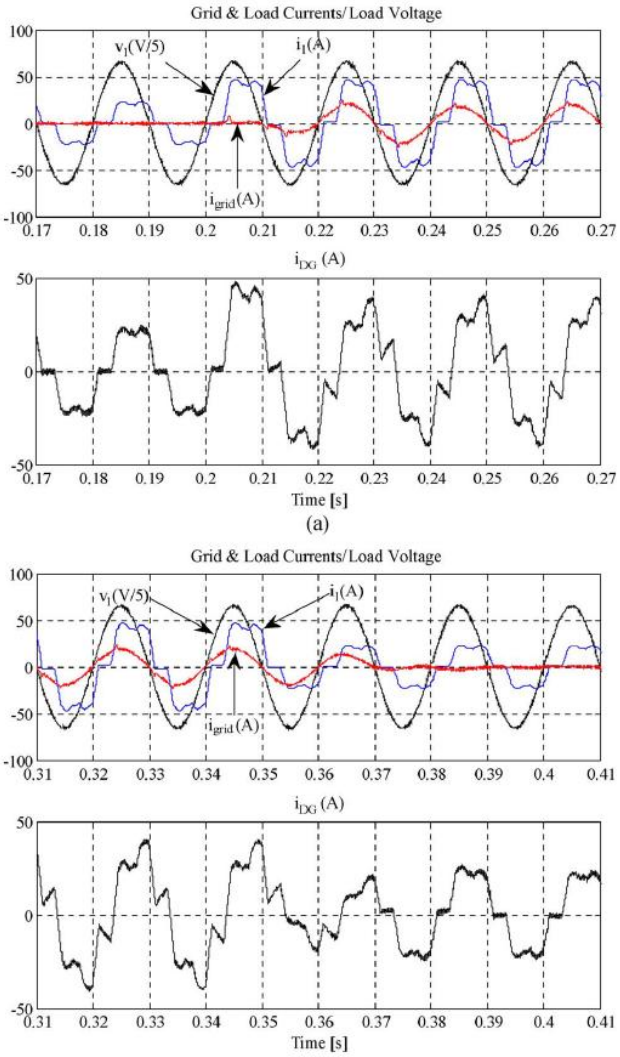

Fig. 9. Grid, load, DG currents, and load voltage (a) before and after connection of additional load and (b) before and after disconnection of additional load

TABLE I
Fundamental and THD values of grid currents

Before Compensation				After Compensation		
Peak Current (A)	I_{grid1}	I_{grid2}	I_{grid3}	I_{grid1}	I_{grid2}	I_{grid3}
Fundamental	47.16	47.23	47.64	17.67	17.73	17.54
THD%	21.39	21.29	21.84	4.26	4.28	4.35

THD of the grid currents while feeding nonlinear loads. The THDs of the grid currents are reduced from 21.39%, 21.29%, and 21.84% before compensation to 4.26%, 4.28%, and 4.35% after compensation, respectively. These results confirm the capability of the proposed DG link to compensate harmonic currents of the nonlinear loads. The trajectories of the load, grid, and DG currents in *α β* representation shows the trajectory of the load currents in *α β* representation, which is required to supply the load, before and after connection of additional load to the PCC. It can be seen that the ac currents are containing some harmonic current distortion for feed forward modulation, so the *α β representation* of those currents is not circular and is hexagonal. In addition, after the second load similar to first load is connected to the ac grid, radius of external hexagonal is exactly two times greater than radius of internal hexagonal.

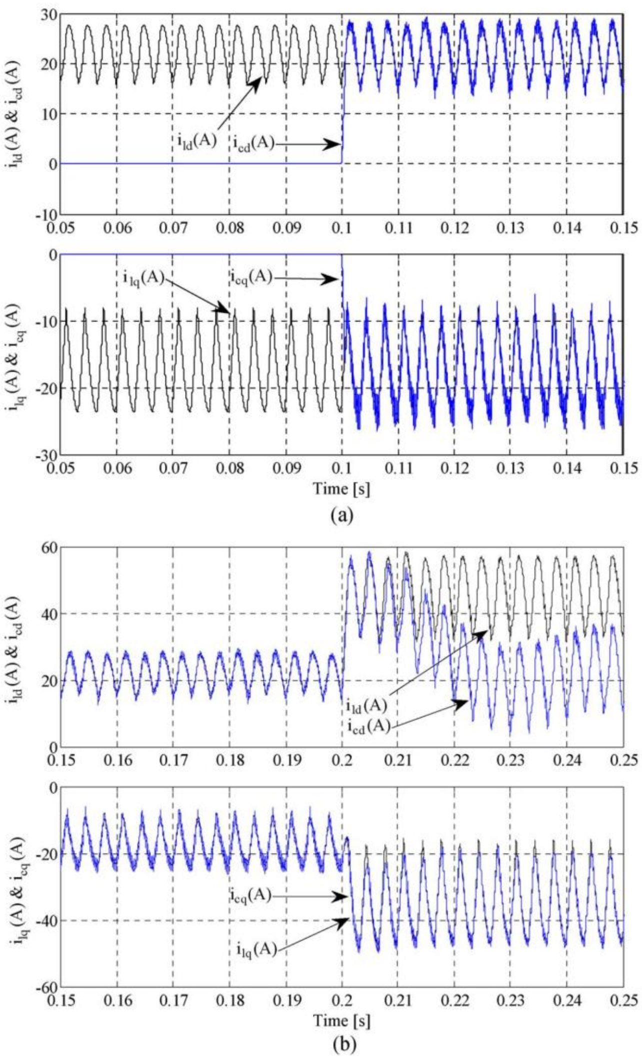

Fig. 10. Reference currents track the load current (a) after interconnection of DG resources and (b) after additional load increment.

B. Connection of DG Link to an Unbalanced Grid

In this section, the ability of proposed DG link to track load current components for unbalanced grid voltage is evaluated. At first, a nonlinear load similar to the prior load is added to the PCC at t = 0.45 s. At t = 0.55 s, the grid voltage is unbalanced.

Fig. 12 shows three-phase grid voltages, load current, grid current, and DG link current. harmonic current components are provided by DG link, and grid currents are maintained sinusoidal during balanced and unbalanced grid voltages. In addition, load voltage and grid current are kept in phase (the grid does not provide reactive current). The proposed control scheme provides balanced current injection from the DG link. Therefore, since the grid voltage unbalance forces unbalanced current in the load, the grid current is unbalanced.

Depending on the power converter current ratings and voltage unbalance severity, it could be possible to compensate the grid currents unbalance by injecting unbalance currents from the DG link, but this is not the purpose of the present control scheme.

All the nonlinear current components are injected by main grid to the nonlinear load. This process is continued until the DG link is connected to the main grid. After connection of DG link to the grid, the grid current becomes zero, and all the active and reactive current components including fundamental and harmonic frequencies are provided by DG link ($i_{grid} = i_{load} - i_{DG}$). It can be seen that the problems due to synchronization between DG and power grid do not exist and DG link can be connected to the proposed grid without any high-current overshoot. The proposed load's current is fed from nonlinear DG link continuously, and this process is continued until another full-wave diode rectifier similar to the prior load is connected to the grid.

V. Conclusion

A multi objective control algorithm for the grid-connected converter-based DG interface has been proposed and presented in this paper. Flexibility of the proposed DG in both steady-state and transient operations has been verified through simulation and experimental results. Due to sensitivity of phase-locked loop to noises and distortion, its elimination can bring benefits for robust control against distortions in DG applications. Also, the problems due to synchronization between DG and grid do not exist, and DG link can be connected to the power grid without any current overshoot. One other advantage of proposed control method is its fast dynamic response in tracking reactive power variations; the control loops of active and reactive power are considered independent. By the use of the proposed control method, DG system is introduced as a new alternative for distributed static compensator in distribution network. The results illustrate that, in all conditions, the load voltage and source current are in phase and so, by improvement of power factor at PCC, DG

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