AN ADVANCED CONTROLLER FOR REDUCTION OF HARMONICS UNDER NON-LINEAR LOADS AND GRID VOLTAGE DISTORTIONS

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Abstract-In this paper we proposed an advanced current control topology for grid-connected operations of distributed generation (DG), which supports the DG to transfer a sinusoidal current into the utility grid despite the distorted grid voltage and nonlinear local load conditions with the help of an advanced controller called as fuzzy logic controller. The proposed current controller is designed with fuzzy logic controller gives better results than the conventional PI controller. Hence the control strategy with the fuzzy logic controller can be adopted to get good response from system. Therefore, the proposed control method can be easily adopted into the traditional DG control system without installation of extra hardware. The proposed control method is analyzed in detail, and its result is verified with MATLAB/SIMLINK software.

Key words: Distributed generation (DG), grid-connected inverter, harmonic compensation, nonlinear load, fuzzy logic controller

INTRODUCTION

Distributed generation, also called on-site generation, dispersed generation, embedded generation, decentralized generation, decentralized energy or distributed energy, generates electricity from many small energy sources. Currently, industrial countries generate most of their electricity in large centralized facilities, such as fossil fuel (coal, gas, or nuclear) or hydropower plants. These plants have excellent economies of scale, but usually transmit electricity long distances and negatively affect the environment. Low pollution is a crucial advantage of combined cycle plants that burn natural gas. The low pollution permits the plants to be near enough to a city to be used for district heating and cooling. Distributed generation is another approach. It reduces the amount of energy lost in transmitting electricity because the electricity is generated very near where it is used, perhaps even in the same building. This also reduces the size and number of power lines that must be constructed. Typical distributed power sources in a Feed-in Tariff (FIT) scheme have low maintenance, low pollution and high efficiencies. In the past, these traits required dedicated operating engineers and large complex plants to reduce pollution. However, modern embedded systems can provide these traits with automated operation and renewable, such as sunlight, wind, and geothermal. This reduces the size of power plant that can show a profit. The use of renewable energy sources, such as wind turbines, photovoltaic, and fuel cells, has greatly increased in recent decades to address concerns about the global energy crisis, depletion of fossil fuels, and environmental pollution problems. As a result, a large number of renewable energy sources have been integrated in power distribution systems in the form of distributed generation (DG). DG systems can offer many advantages over traditional power generation, such as small size, low cost, high efficiency, and clean electric power generation. A DG system is typically operated in a grid-connected mode where the maximum available power is extracted from energy sources and transferred to the utility grid. In addition, to exploit full advantages of a DG system, the DG can be also equipped and operated with local loads, where the DG supplies power to the local load and transfers surplus power to the grid. In both configurations, i.e., with and without the local load, the prime objective of the DG system is to transfer a high-quality current (grid current) into the utility grid with low harmonic distortion.

To eliminate the adverse effect of the distorted grid voltage on the grid current quality, several harmonic compensation methods have been introduced. In a novel compensation approach for reducing the THD of the grid current under distorted grid voltage is introduced. In this method, the harmonic components in the grid voltage are extracted, and the Cauchy–Schwarz inequality theory is adopted to find the minimum point of the grid current THD. The grid current quality therefore relies heavily on the accuracy of the grid voltage harmonic analysis; if the harmonic components in the grid voltage are varied, it is difficult to maintain a good grid current quality. Moreover, the searching algorithm requires a large calculation time and
can operate only offline. In and , several selective harmonic compensators are developed using a resonant controller, in which the resonant controller tuned at the sixth multiple of the fundamental frequency is added to eliminate the effect of fifth and seventh harmonic grid voltages on the grid current quality.

The grid current quality can be improved, due to the fuzzy logic controllers. However, if higher order harmonics are taken into account in conventional technique we used more controllers to reduce harmonics but increase.of controller’s leads to the complexity of the control system. To improve the grid current quality with a simplified control scheme, in this paper control is done by the fuzzy logic controller. The control scheme consists of a Fuzzy controller, a limiter, and a three phase sine wave generator for the generation of the internal structure of the control circuit. The control scheme consists of a Fuzzy controller, a limiter, and a three phase sine wave generator for the generation of reference currents and switching signals. The peak value of the reference current is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through a Fuzzy controller, which contributes to the zero steady error in tracking the reference current signal. A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed either by expert experience or with a knowledge database. Firstly, the input Error ‘E’ and the change in Error ‘4E’ have been placed with the angular velocity to be used as the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control current I_max.

Along with grid voltage distortion, the presence of nonlinear loads in the local load of the DG also causes a negative impact on the grid current quality. To address this problem, the local load current measurement and a load current feed forward loop are regularly adopted. Although these compensation methods are effective in improving grid current quality, the requirement of additional hardware, specifically the current sensor for measuring the local load current, is the main drawback of this control method. Furthermore, most aforementioned studies consider and separately tackle the impact of distorted grid voltage or the nonlinear local load; none of them simultaneously takes into account those issues.

To overcome the limitations of aforementioned studies, this paper proposes an advanced current control strategy for the grid-connected DG, which makes the grid current sinusoidal by simultaneously eliminating the effect of nonlinear local load and grid voltage distortions. First, the influence of the grid voltage distortions and nonlinear local load on the grid current is determined. Then, an advanced control strategy is introduced to address those issues. The proposed current controller is designed in the d–q reference frame and is composed of fuzzy logic controllers the proposed system has better results compared with the conventional controller.

**System configuration and analysis of grid voltage distortion and nonlinear local load**

Fig. 2 shows the system configuration of a three-phase DG operating in grid-connected mode. The system consists of a dc power source, a voltage-source inverter (VSI), an output LC filter, local loads, and the utility grid. The purpose of the DG system is to supply power to its local load and to transfer surplus power to the utility grid at the PCC. To guarantee high-quality power, the current that the DG transfers to grid (i_g) should be balanced, sinusoidal, and have a low THD value. However, because of the distorted grid voltage and nonlinear local load that typically exist in the power system, it is not easy to satisfy these requirements.

**Rule Base:** The elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse input/output variables, while in the steady state, small errors need fine control, which requires fine input/output variables. Based on this, the elements of the rule table are obtained as shown in table 1.
Effect of Grid Voltage Distortion

To assess the impact of grid voltage distortion on the grid current performance of the DG, a model of the grid-connected DG system is developed, as shown in Fig. 3. In this model, the VSI of the DG is simplified as voltage source \( v_i \). The inverter transfers a grid current \( i_g \) to the utility grid \( v_g \). For simplification purpose, it is assumed that the local load is not connected into the system. In Fig. 3(a), the voltage equation of the system is given as

\[
v_i - v_g - L_f \frac{di_g}{dt} - R_f i_g = 0 \tag{1}
\]

Where \( R_f \) and \( L_f \) are the equivalent resistance and inductance of the inductor \( L_f \), respectively.

If both the inverter voltage and the grid voltage are composed of the fundamental and harmonic components as (2), the voltage equation of (1) can be decomposed into (3) and (4), and the system model shown in Fig. 3(a) can be expressed as Fig. 3(b) and (c), respectively. That is

\[
v_i = v_{i1} + \sum_{h \neq 1} v_{ih}
\]

\[
v_g = v_{g1} + \sum_{h \neq 1} v_{gh} \tag{2}
\]

\[
v_{i1} - v_{g1} - L_f \frac{di_{g1}}{dt} - R_f i_{g1} = 0 \tag{3}
\]

\[
\sum_{h \neq 1} v_{ih} - \sum_{h \neq 1} v_{gh} - L_f \frac{d(\sum_{h \neq 1} i_{gh})}{dt} - R_f \sum_{h \neq 1} i_{gh} = 0 \tag{4}
\]

From (4), due to the existence of the harmonic components \( \sum_{h \neq 1} v_{gh} \) in the grid voltage, the harmonic currents \( \sum_{h \neq 1} i_{gh} \) are induced into the grid current if the DG cannot generate harmonic voltages \( \sum_{h \neq 1} v_{gh} \) that are exactly the same as \( \sum_{h \neq 1} i_{gh} \). As a result, the distorted grid voltage at the PCC causes non sinusoidal grid current if the current controller cannot handle harmonic grid voltage \( \sum_{h \neq 1} v_{gh} \).

Effect of Nonlinear Local Load

Fig. 4. shows the model of a grid-connected DG system with a local load, whereby the local load is represented as a current source \( i_L \), and the DG is represented as a controlled current source \( i_{DG} \). According to Fig. 4, the relationship of DG current \( i_{DG} \), load current \( i_L \), and grid current \( i_g \) is described as

\[
i_{DG} = i_L + i_g \tag{5}
\]
Assuming that the local load is nonlinear, e.g., a three-phasediode rectifier, the load current is composed of thefundamental and harmonic components as

$$i_L = i_{L1} + \sum_{h=1}^{\infty} i_{Lh}$$  \hspace{1cm} (6)

Where $i_{L1}$ and $i_{Lh}$ are the fundamental and harmoniccomponents of the load current, respectively. Substituting (6) into (5), we have

$$i_k = i_{DG} - \left(i_{L1} + \sum_{h=0}^{\infty} i_{Lh}\right)$$  \hspace{1cm} (7)

From (7), it is obvious that, in order to transfersinusoidal grid current into the grid, DG current $i_{DG}$ should includethe harmonic components that can compensate the load current harmonics. Therefore, it is important to design an effective and low-cost current controller that can generate the specific harmonic components to compensate the load current harmonics. Generally, traditional current controllers, such as the PI or PR controllers, cannot realize this demand because they lack the capability to regulate harmonic components.

**Proposed Control Scheme**

To enhance grid current quality, an advanced current control strategy, with the fuzzy logic controller is shown in Fig. 5. Although there are several approaches to avoid the grid voltage sensors and a phase-locked loop (PLL), Fig. 5 contains the grid voltage sensor and a PLL for simple and effective implementing of the proposed algorithm, which is developed in the $d-q$ reference frame. The proposed control scheme is composed of three main parts: the PLL, the current reference generation scheme, and the current controller. The operation of the PLL under distorted grid voltage has been investigated. As shown in Fig. 5, the control strategy operates without the local load current measurement and harmonic voltage analysis on the grid voltage. Therefore, it can be developed without requiring additional hardware. Moreover, it can simultaneously address the effect of the nonlinear local load and distorted grid voltage on the grid current quality.

A. Current Reference Generation

As shown in Fig. 5, the current references for the current controller can be generated in the $d-q$ reference frame based on the desired power and grid voltage as follows

$$i_{gd}^* = \frac{2}{3} P^* - \frac{2}{3} Q^*$$  \hspace{1cm} (8)

Where $P^*$ and $Q^*$ are the reference active and reactive power, respectively. $V_{gd}$ represents the instantaneous grid voltage in the $d-q$ frame, and $I_{gd}$ and $I_{gq}$ denote the direct and quadrature components of the grid current, respectively.

Under ideal conditions, the magnitude of $V_{gd}$ has a constant value in the $d-q$ reference frame because the grid voltage is pure sinusoidal. However, if the grid voltage is distorted, the magnitude of $V_{gd}$ no longer can be a constant value. As a consequence, reference current $I_{gd}$ and $I_{gq}$ cannot be constant in (8). To overcome this problem, a low pass filter (LPF) is used to obtain the average value of $V_{gd}$, and the $d-q$ reference currents are modified as follows

$$i_{gd}^* = \frac{2}{3} P^* - \frac{2}{3} Q^*$$  \hspace{1cm} (9)

Where $V_{gd0}$ is the average value of $V_{gd}$ which is obtained through the LPF in Fig. 5.

B. Current Controller

An advanced current controller is proposed by using FLC in the $d-q$ reference frame. The block diagram of the current controller is shown in Fig. 6.
Fig. 6. Block diagram of the current controller.

**ABOUT FUZZY LOGIC CONTROLLER**

A fuzzy inference system (or fuzzy system) basically consists of a formulation of the mapping from a given input set to an output set using fuzzy logic. This mapping process provides the basis from which the inference or conclusion can be made. A fuzzy inference process consists of the following steps:

Step 1: Fuzzification of input variables
Step 2: Application of fuzzy operator (AND, OR, NOT) in the IF (antecedent) part of the rule

Step 3: Implication from the antecedent to the consequent (THEN part of the rules)
Step 4: Aggregation of the consequents across the rules
Step 5: Defuzzification

The crisp inputs are converted to linguistic variables in fuzzification based on membership function (MF). An MF is a curve that defines how the values of a fuzzy variable in a certain domain are mapped to a membership value \( \mu \) (or degree of membership) between 0 and 1. A membership function can have different shapes. The simplest and most commonly used MF is the triangular-type, which can be symmetrical or asymmetrical in shape. A trapezoidal MF has the shape of a truncated triangle. Two MFs are built on the Gaussian distribution curve: a simple Gaussian curve and a two-sided composite of two different Gaussian distribution curves. The bell MF with a flat top is somewhat different from a Gaussian function. Both Gaussian and bell MFs are smooth and non-zero at all points. The implication step helps to evaluate the consequent part of a rule. There are a number of implication methods in the literature, out of which Mamdani and TS types are frequently used. Mamdani proposed this method which is the most commonly used implication method. In this, the output is truncated at the value based on degree of membership to give the fuzzy output.

**TABLE 2**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage</td>
<td>110 V (rms)</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Rated output power</td>
<td>5 Kw</td>
</tr>
<tr>
<td>Dc link voltage</td>
<td>350 V</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>9 KHz</td>
</tr>
<tr>
<td>Output filter inductance</td>
<td>0.7 mH</td>
</tr>
<tr>
<td>Output filter resistance</td>
<td>0.1Ω</td>
</tr>
<tr>
<td>Output filter capacitance</td>
<td>27μF</td>
</tr>
<tr>
<td>Load of three phase diode rectifier</td>
<td>R=30Ω C=2200μF</td>
</tr>
<tr>
<td>Three phase linear load</td>
<td>R=30Ω</td>
</tr>
</tbody>
</table>

**SIMULATION RESULTS**

A simulation model of the DG system is built by MATLAB simulation software to verify the effectiveness of the proposed control method. The system parameters are given in Table 2. In the simulation, three cases are taken into account.

1) Case I: The grid voltage is sinusoidal and the linear local load is used.
2) Case II: The grid voltage is sinusoidal and the nonlinear local load is used.
3) Case III: The grid voltage is distorted and the nonlinear local load is used.

In Cases I and II, the grid voltage is assumed as a pure sinusoidal waveform. In Case III, the distorted grid voltage is supplied with the harmonic components: 3.5% 5th harmonic, 3% 7th harmonic, 1% 11th harmonic, and 1% 13th harmonic. The THD of grid voltage is about 4.82%. In all test cases, the reference grid current is set at $i_{gd}\ast = 10$ A and $i_{gd}\ast = 0$. Simulation results are shown in fig. 8, and their THD values are shown in fig. 9.
Fig. 9. THD for proposed FLC current controller: (a) Case I; (b) Case II; and (c) Case III.

In addition, to assess the feasibility of the proposed current controller under grid frequency variations, simulation results of the proposed FLC current controller, when the grid frequency changes from 50 to 49 Hz and from 50 to 51 Hz, are illustrated in Fig. 10(a) and (b), respectively. In Fig. 10, the PLL quickly detects the grid frequency variation and accurately compensates it within a short period of time, i.e., less than 10 ms without any influence on the grid current. Therefore, we can say that the proposed current controller is able to maintain a high-quality grid current even under the grid frequency variations.

**CONCLUSION**

Here we proposed a new current control strategy for the grid-connected DG to eliminate the effect of grid voltage distortion and nonlinear local load on the grid current. The simulation results established that the DG with the proposed current controller can sufficiently transfer a sinusoidal current to the utility grid, despite the nonlinear local load and distorted grid voltage conditions. The proposed fuzzy based current control scheme can be
implemented without the local load current sensor and harmonic analysis of the grid voltage; therefore, it can be easily integrated in the conventional control scheme without installation of extra hardware. Despite the reduced number of current sensors, the quality of the grid current is significantly improved: the THD value of the grid current is decreased considerably compared with that achieved by using the conventional PI current controller. In addition, the proposed current controller also maintained a good quality of grid current under grid frequency variations. Moreover, the dynamic response of the grid current controller was also improved with the help of the proposed fuzzy logic based current controller. That can shown here with the help of simulation results.

REFERENCES

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