A Newly-Developed Control Method for Harmonic Mitigation in PV Grid-Connected Inverters Under Electric Arc Furnaces in Industrial Microgrids

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Abstract. A microgrid (MG) is a discrete energy system consisting of distributed generation (DG) and loads or nonlinear loads that is able to operate at the same time the main grid is operating. The DG units can operate in parallel with the main grid or in an MG mode. The unbalanced and nonlinear characteristics of numerous loads that are in connection with the power system have the potential to bring about some problems, in terms of power quality, which can affect other consumers. For instance, the electric arc furnaces (EAFs) cause considerable problems for power quality. The instantaneous power theory \((pq)\) and the coordinate formulation \((dq)\) are proposed in this paper for harmonic current compensation for PV grid-connected inverters and EAF in MGs. With the proposed control strategy under EAF conditions, the total harmonic distortions of the system current were decreased from 38.24% to 3.25%, which duly satisfies the IEEE 519-1992 standard.

1. Introduction

The warning increase of CO2 emissions and global warming are two significant signs of climate change, which indicates a pressing need to find out innovative ways to generate energy using renewable sources. A solution to this problem is producing electricity in a place closer to final consumers, which is recognized as a distributed energy generation. This strategy decreases our dependency on long-distance power lines. Making a reliable connection between renewable energy sources and the utility grid, however, can result in new challenges.

New Renewable Energy Sources (RESs), such as Photovoltaic cell (PV), is often intermittent [1]. These energy systems can be combined or connected to a local energy storage system to maintain a continuous power flow between the mains grid and the local network [2].
When smaller producers are connected to grids via distributed electricity generation methods and can produce their own share of electricity, planning for this increase in RESs is one of the unavoidable future problems. Nonetheless, integrating RESs has become a priority in these stand-alone distribution networks. The diffusion of RESs with the MG concept has evolved into clusters of loads and paralleled RESs that can operate as a single power system to provide power to its local area [3].

Fossil energy reserves are getting exhausted due to a substantial increase of demands for electrical energy in current world [4]. On the other hand, the currently-used energy resources must be exploited more efficiently and cautiously because of the high price of energy in today’s (and probably future) market. As a result, power electronic converters are getting more and more popular due to their high capacity for converting and controlling electrical power in a broad range from milliwatts to gigawatts using power semiconductor devices [5]. Nowadays, power electronics are processing over 70% of all electricity [6]. For the purpose of minimizing the energy waste, enhancing power quality, and reducing the cost of power production processes and power distribution/transmission, need to power electronics systems with a high degree of efficiency, sustainability, reliability, and quality [7]. With increasing power densities, challenges related to the quality of the power electronic systems have been more significant. The power electronic converters are typically utilized in microgrids aiming at controlling the power flow, and effectively converting power into appropriate DC or AC form [8].

A great deal of research has been conducted into power system for the purpose of attenuating the damping of low-frequency oscillations, whereas literature lacks adequate research into the use of nonlinear loads like EAFs and the way they can affect the network power quality [9].

Load flow calculations are vital for power flows, voltage profile, and losses determination [10]. These calculations are also used to assess voltage regulation issues and the basic capacity that is incorporated into the distributed generator interconnection. These calculations can also support other analyses, such as reliability, contingency, as well as power quality or transients. By finalizing these calculations, the model of the power system can be tuned according to its operational limits [11]. Adjustments may consist of selecting different transformer taps, generator working setpoints, reactive power compensators, and spinning reserve.

The addition of significant levels of renewable generators, such as photovoltaics (PVs), may increase the complexity of these analyses because of the uncertain nature of the energy sources [12]. For example, the time and location dependency of wind generators require extra care when combined with feeder location and load variability. Thus, further studies are required to determine the operating conditions that the new power systems will experience. This situation gets even worse when energy storage devices are employed. In such conditions, the calculations may be done over a longer period.

DG creates several challenges in load flow calculations such as modeling of the transmission or subtransmission system, simulating the equipment’s for voltage-control, embedding single and two-phase lines, single-phase loads, which in the general view cause unbalanced systems in calculations. Therefore, a proper load flow tool for a system containing distributed renewable generation, besides the conventional power system components, must contain a vast number of various generation and energy storage models combined with analysis capabilities.

2. Grid-connected inverter control methods

2.1. Instantaneous Reactive Power Theory

In 1984, Akagi pioneered the control method on the basis of the instantaneous reactive power theory. This method aimed at fixing the instantaneous active power in the feeding network. Instantaneous active and reactive power’s theory was originally on the basis of Clarke Transform. The instantaneous three-phase currents and voltages are easily converted into the αβ orthogonal coordinates using Clarke Transform [13, 14]. Where the α and β, axes are the orthogonal coordinates. Presently, vα and iα are on the α axis, vβ and iβ are on the axis β. The following relations show this conversion:
\[ \mathbf{v} = \begin{bmatrix} v_a \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0 \end{bmatrix} \begin{bmatrix} v_a \\ v_\beta \\ v_c \end{bmatrix} \] (1)

\[ \mathbf{i} = \begin{bmatrix} i_a \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_\beta \\ i_c \end{bmatrix} \] (2)

The instantaneous real power \( p \) and the instantaneous imaginary power \( q \) is defined as follows:

\[ p_{a\beta} = v_a i_a + v_b i_b + v_c i_c \] (3)

In this method, a set of currents \( i_a, i_b, i_c \) and voltages \( v_a, v_b, v_c \) from phase coordinates are first transferred. Furthermore, the three-phase instantaneous active power can be obtained through the normal relations among the coordinates abc as follows:

\[ p_{a\beta} = v_a i_a + v_b i_b + v_c i_c \] (4)

Instantaneous three-phase reactive power in \( a\beta \) reference frame is defined as:

\[ q_{a\beta} = v_a i_a + v_\beta i_\beta \] (5)

Active \( p \) and reactive \( q \) powers are defined as:

\[ \begin{bmatrix} p_{a\beta} \\ q_{a\beta} \end{bmatrix} = \begin{bmatrix} v_a & v_\beta \\ -v_\beta & v_a \end{bmatrix} \begin{bmatrix} i_a \\ i_\beta \end{bmatrix} \] (6)

Equation (6) can be rewritten as:

\[ \begin{bmatrix} i_a \\ i_\beta \end{bmatrix} = \begin{bmatrix} v_a & v_\beta \\ -v_\beta & v_a \end{bmatrix}^{-1} \begin{bmatrix} p_{a\beta} \\ q_{a\beta} \end{bmatrix} \] (7)

In (6) \( v_a * i_a \) and \( i_\beta * v_\beta \) obviously mean instantaneous power since they are defined by the product of the instantaneous voltage in one axis and the instantaneous current in the same axis. As a result, using inverse transformation, current components in \( a\beta \) can be calculated using active and reactive instantaneous powers as:

\[ \begin{bmatrix} i_a \\ i_\beta \end{bmatrix} = \frac{1}{v_a^2 + v_\beta^2} \begin{bmatrix} v_a & -v_\beta \\ v_\beta & v_a \end{bmatrix} \begin{bmatrix} p_{a\beta} \\ q_{a\beta} \end{bmatrix} \] (8)

The \( v_a i_a \) and \( v_\beta i_\beta \) components in above are active power elements.

2.2. DQ Synchronous Reference Frame Control

Instantaneous voltage and current quantities are transformed to synchronous reference frame with Park’s transformation matrix \( [L] \) which is as (9).

\[ [L] = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 1 & 1 \\ \sqrt{2} & \sqrt{2} & \sqrt{2} \\ \cos \theta_a(t) & \cos \theta_b(t) & \cos \theta_c(t) \\ -\sin \theta_a(t) & -\sin \theta_b(t) & -\sin \theta_c(t) \end{bmatrix} \] (9)

\[ \theta_j(t) = \theta \left( t - \frac{2\pi}{3} (j - 1) \right), \quad j = a, b, c \] (10)

Considering \( \theta_j(t) = \omega t \), \( 0a\beta \) components are transformed to \( 0dq \) components using (11) as:
\[
\begin{bmatrix}
    i_0(t) \\
    i_d(t) \\
    i_q(t)
\end{bmatrix} = \frac{1}{e_{a\beta}}
\begin{bmatrix}
    e_{a\beta} & 0 & 0 \\
    0 & e_\alpha & e_\gamma \\
    0 & -e_\beta & e_\alpha
\end{bmatrix}
\begin{bmatrix}
    i_0(t) \\
    i_d(t) \\
    i_q(t)
\end{bmatrix}
\] (11)

So that voltage \(d\)-component is calculated as:

\[e_d(t) = |E(t)| = e_{a\beta} = \sqrt{e_\alpha^2 + e_\beta^2} \] (12)

Fundamental positive sequence current component in ABC frame is transformed into a DC component in 0dq frame. Remaining harmonic current components including negative and zero sequences are appearing as alternative components in 0dq frame. It means that there is a frequency shift \((\omega)\) in the mentioned components. Consequently, the compensator reference current is \(I_{cref}\) is as:

\[I_{cref}(t) = I_L(t) - I_s(t) \] (13)

\[I_s = \frac{1}{i_{ld}}
\begin{bmatrix}
    e_\alpha \\
    e_\beta
\end{bmatrix} \] (14)

Considering (13) and (14), compensator reference 0\(\alpha\beta\) current is as:

\[
\begin{bmatrix}
    i_{L0}(t) \\
    i_{Ld}(t) \\
    i_{Lq}(t)
\end{bmatrix} = \left( \frac{P_{L\alpha\beta}(t)}{e_{a\beta}} \right) \frac{1}{e_{a\beta}} \begin{bmatrix}
    0 \\
    e_\alpha(t) \\
    e_\beta(t)
\end{bmatrix} \] (15)

In contrast to other methods, active power is necessary at the compensator side in 0dq control method which can be accomplished by a correction in compensator reference current (1).

3. Simulation results

Fig. 1 displays the single-line diagram of the system, in which the microgrid system that is considered in the present paper is depicted. There was one DG, while the others were converter interfaced DGs (with PV). The microgrid was able to operate in the grid-connected mode of operation. A basic photovoltaic cell is a low-power electric generator.

![Figure 1. Configuration of the system](image)

The MATLAB Simulink was used to perform the required simulations, where system voltage is assumed sinusoidal. Figure 2 displays the system waveforms with no compensation; The PV source deliver a nonsinusoidal current to the system while nonlinear loads flow harmonic currents from the system. Nonlinear loads including electric arc furnace make a system current nonlinear and unbalanced as shown in Figure 3.
Figure 2. Current waveforms without compensation.

At 4 seconds, proposed control methods are connected to the system; system current harmonics and unbalance is compensated. Remember that $p-q$ and $d-q$ control methods are used in Figure 3.

Figure 3. Configuration Current waveforms after using $p-q$ and $d-q$ control methods.

The grid-connected inverter is connected, the source current becomes balanced and sinusoidal. GCI demonstrated in Fig. 3 using $dq$ control method since the system voltage is sinusoidal, there is not a major difference between $pq$ and $dq$ control methods simulation waveforms. For instance, in the $dq$ control methods, there is a need for phase detection, which increases the calculations and complex control method while this circuit is not necessary at $pq$ method. With no compensation, system current THD was recorded 38.24 %, while with implementing compensation, it showed a reduction down to 3.25 % in the $pq$ method. But in $dq$ it was 11.4 %.

Table 1. Parameters of the System.

| Parameter                           | Values  |
|-------------------------------------|---------|
| AC supply voltage                   | 35 V    |
| AC inductor of the diode rectifier: | 5mH     |
| $L_{ac}$                             |         |
| AC resistor of the diode rectifier: | 3 Ω     |
| $R_{ac}$                             |         |
| System resistance: $R_s(\Omega)$    | 0.3     |
4. Conclusion
With regard to the growth of power electronic devices and non-linear loads, power filters are used as one of the methods to compose harmonics and reactive power due to non-linear loads. Combining active and passive filters (combined filters) is an efficient and economical method. This study proposes the use of the grid-connected inverter control method, including instantaneous power theory (pq) and the coordinate formulation (dq). Studies on a group of nonlinear loads (electric arc furnaces) as harmonic current sources as well as distributed generation source (photovoltaic) show that with the proposed control strategy under EAF conditions, the total harmonic distortions of the system current were decreased from 38.24% to 3.25%.

Acknowledgements
The authors wish to thank the Ministry of Education, Universiti Teknologi Malaysia, and Universiti Sriwijaya (Grant numbers 4F828, 01M44, 18H10, 4B345, 4B379 and 04E54) for the financial support.

References
[1] Naderipour A, Abdul-Malek Z, Vahid MZ, Seifabad ZM, Hajivand M, Arabi-Nowdeh S. Optimal, Reliable and Cost-Effective Framework of Photovoltaic-Wind-Battery Energy System Design Considering Outage Concept Using Grey Wolf Optimizer Algorithm—Case Study for Iran. IEEE Access. 2019;7:182611-23.
[2] Naderipour A, Abdul-Malek Z, Heidari Gandoman F, Nowdeh SA, Shiran MA, Hadidian Moghaddam MJ, et al. Optimal designing of static var compensator to improve voltage profile of power system using fuzzy logic control. Energy. 2020;192:116665.
[3] Lasseter B, editor Microgrids [distributed power generation]. 2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.01CH37194); 2001 28 Jan.-1 Feb. 2001.
[4] Naderipour AR, editor Voltage and current compensation in dispersed generation systems. 2010 First Power Quality Conference; 2010 14-15 Sept. 2010.
[5] Naderipour AR, editor A hybrid solution to improve power quality in dispersed generation systems. 2010 First Power Quality Conference; 2010 14-15 Sept. 2010.
[6] Bahman AS. Multidisciplinary Modelling Tools for Power Electronic Circuits: with Focus on High Power Modules. Department of Energy Technology, Aalborg University: Aalborg University; 2015.
[7] Naderipour A, Abdul-Malek Z, Abohamzeh E, Ramachandaramurthy VK, Miveh MR, editors. Control strategy of Grid-Connected PV Inverters in Microgrid with Nonlinear Operating Conditions. 2018 IEEE 7th International Conference on Power and Energy (PECon); 2018 3-4 Dec. 2018.
[8] Sharkh SM, Abu-Sara MA, Orfanoudakis GI, Hussain B. Power Electronic Converters for Microgrids: Wiley; 2014.
[9] Ozgun O, Abur A, editors. Development of an arc furnace model for power quality studies. 1999 IEEE Power Engineering Society Summer Meeting. Conference Proceedings (Cat.
No.99CH36364); 1999 18-22 July 1999.

[10] Hertem DV, Verboomen J, Purchala K, Belmans R, Kling WL, editors. Usefulness of DC power flow for active power flow analysis with flow controlling devices. The 8th IEE International Conference on AC and DC Power Transmission; 2006 28-31 March 2006.

[11] Kulkarni N, Kamalasadan S, Ghosh S. An Integrated Method for Optimal Placement and Tuning of a Power System Stabilizer Based on Full Controllability Index and Generator Participation. *IEEE Trans Ind Appl*. 2015;51(5):4201-11.

[12] Abdel-Nasser M, Mahmoud K. Accurate photovoltaic power forecasting models using deep LSTM-RNN. *Neural Computing and Applications*. 2019;31(7):2727-40.

[13] Akagi H, Kanazawa Y, Nabae A. Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components. *IEEE Trans Ind Appl*. 1984;IA-20(3):625-30.

[14] Fang Zheng P, Ott GW, Adams DJ. Harmonic and reactive power compensation based on the generalized instantaneous reactive power theory for three-phase four-wire systems. *IEEE Trans Pow Electr*. 1998;13(6):1174-81.