Research paper

Frequency and Voltage Control of an Inverter-Based DG Using Adaptive Fuzzy-Sliding Mode Controller

E. Limouchi¹, S.A. Taher¹, B. Ganji¹*,

Faculty of Electrical and Computer Engineering, University of Kashan, Iran.

Introduction

Recently, microgrid and distributed generation (DG) are two well-known concepts in the power distribution system. The microgrid is collection of distribution generations which work together for safe and economic power transmission. Some new challenges about operation of microgrid and control of voltage and frequency are presented in [1]-[3]. The effects of energy storage tools on microgrid dynamic response are studied in [4]. To regulate voltage and frequency of microgrid in connected mode, direct-quadrature current control method is proposed in [5]-[6]. To improve the performance and the stability of the power system, various control methods are usually introduced [7]. A disturbance observer method is used in [8] to overcome the weaknesses of droop control strategy for load sharing and voltage stability in a DC microgrid. For control of power system, the intelligent algorithms such as artificial neural networks (ANN) are also used frequently [9][10]. In [11], ANN is used to assess voltage stability. Using intelligent techniques such as fuzzy logic (FL) and ANNs, control of power systems is reported in [12].

Despite multiple advantages, microgrid leads to new
problems such as change of power flow pattern, increase of high frequency harmonics due to using inverter-based DG, and increasing frequency and voltage fluctuations resulted from the changing nature of renewable energy sources [13]. Renewable energy sources are usually connected to microgrid by power electronic interfaces such as inverters. In islanding mode of microgrid, voltage source inverter (VSI) is used more [14]. This in case, microgrid frequency and voltage are controlled through local control loops. To avoid from flow circulation among parallel inverters connected to microgrid, control strategies based on droop characteristic are usually applied [15].

Different methods are recommended to control inverters output power along with power management in past years. Many researchers have also worked on design of controller. For instance, proportional-integral controller (PI) in [16]-[17], proportional resonance [18][19], fuzzy control in [20]-[21] and predictive control in[22]-[23] can be observed. The conventional PI is a simple controller with easy performance but it is so sensitive to change of the system parameters. In addition, PI regulation is complex. One way to control active power of the generator is the sliding mode control that has a high speed in compared with PI. The sliding mode control is a robust method which is effective in uncertainties and external disturbances [24]. At the time of microgrid islanding, appropriate control structure is required to achieve objectives such as voltage and frequency control [25]. The reduction of total harmonic distortion (THD) in output voltage of the inverter is another goal [26]. In the present paper, AFSMC method is introduced to control voltage and frequency in microgrid. In the following, different types of droop control methods including conventional and generalized droop control are described in next section. The generalized droop control method based on adaptive fuzzy-sliding mode is then suggested and it is introduced in the third section. To evaluate performance of the proposed method, the simulation results are then presented. Finally, the paper is concluded in the last section.

**Droop Control**

**A. The conventional droop control**

A simple microgrid depicted in Fig. 1 is considered here in which the DG is connected to load through a line with Z impedance. As illustrated from this figure, active and reactive power in S point can be stated as follows:

\[
P = \frac{V_s^2}{Z} \cos \theta - \frac{V_s V_l}{Z} \cos(\theta + \delta) \tag{1}
\]

\[
Q = \frac{V_s^2}{Z} \sin \theta - \frac{V_s V_l}{Z} \sin(\theta + \delta) \tag{2}
\]

where \( \theta \) is angle related to the line impedance. Considering \( Ze^{\delta}=R+jX \), (1) and (2) can be written as follows:

\[
P = \frac{V_s}{R^2 + X^2} \left[ R(V_s - V_l \cos \delta) + XV_l \sin \delta \right] \tag{3}
\]

\[
Q = \frac{V_s}{R^2 + X^2} \left[ -RV_l \sin \delta + X(V_s - V_l \cos \delta) \right] \tag{4}
\]

The above equations show that output voltage of inverter and the power angle (\( \delta \)) depend on active and reactive powers. Assuming \( X>>R \) and a very small power angle, we have:

\[
\delta = \frac{XP}{V_s V_l}, \quad V_s - V_l = \frac{XQ}{V_s} \tag{5}
\]

With regard to (5), it is illustrated that \( P \) must be controlled to regulate \( \delta \) while \( V_s \) can be controlled through \( Q \) for an inductive microgrid. In other words, the reactive power controls output voltage of the inverter and active power controls system frequency. These control strategies are known as \( Q/V \) and \( P/f \), respectively. With considering the above issues, two ordinary equations can be defined for controlling \( Q/V \) and \( P/f \) with applying linear approximation:

\[
f f_q = k_p (P - P_0) \tag{6}
\]

\[
V_s - V_{so} = k_q (Q - Q_0) \tag{7}
\]

where \( f_0 \) and \( V_{so} \) are the rated voltage and frequency of the microgrid, and \( k_p \) and \( k_q \) are droop coefficients of DG’s active and reactive power. With regard to (6) and (7), if inverter’s frequency or voltage changes for any reason, this effect can be observed in active and reactive power of inverter output. The appropriate deviation value of frequency and voltage can be obtained through droop characteristics. This primary control provides a quick control action to maintain moment balance between production and consumption. Despite of changes in the frequency index and the pulse wide modulation (PWM) voltage of generator, microgrid voltage and frequency are kept in the nominal range. For a resistive microgrid (\( X<<R \)), (5) is modified as follows:

\[
\delta = \frac{RQ}{V_s V_l}, \quad V_s - V_l = \frac{PR}{V_s} \tag{8}
\]

The relationship between reactive power and power
angle and also between active power and voltage are illustrated in (8). By frequency regulation, power angle is controlled automatically. Therefore, in resistant microgrid, droop control techniques of $Q/f$ and $P/V$ are required to control voltage and frequency, respectively. These methods are based on independency of voltage changes and frequency deviation. It is noted that these two factors (voltage and frequency) are dependent on the line parameters.

B. Generalized droop control

Generally, both $R$ and $X$ should be considered for the droop control [9]. As a result, the corrected active and reactive powers are stated as follows:

$$P = \frac{X}{Z} P - \frac{R}{Z} Q$$

$$Q = \frac{R}{Z} P + \frac{X}{Z} Q$$

(9)

(10)

With defining $K_R$ equals to $R/X$ and using (6), (7), (9) and (10), the following equations are resulted:

$$P = \frac{X}{Z} [K_R \Delta f + P_0 - K_R \Delta V_S + K_R Q_0]$$

$$Q = \frac{R}{Z} P = \frac{X}{Z} [K_R \Delta f + K_R P_0 + K_R \Delta V_S + Q_0]$$

(11)

(12)

where $K_R = 1/k_p$, $K_V = 1/k_q$ and $\Delta f$ and $\Delta V$ are frequency deviation and inverter voltage, respectively. In (11) and (12), $K_R$ index is defined to show resistance line percentage. This index helps us to understand simultaneous control of voltage and frequency. After performing algebraic calculations on (11) and (12), the following expressions are obtained:

$$\Delta f = \frac{1}{K_f} \left[ \frac{Z}{X} P' - P_0 \right] + K_p K_V \frac{\Delta V_S + K_R Q_0}{K_f}$$

$$\Delta V = \frac{1}{K_V} \left[ \frac{Z}{X} Q' - Q_0 \right] - K_r K_f \frac{\Delta f - K_r P_0}{K_V}$$

(13)

(14)

From (13), it is obvious that $K_f$ influences on weighted coefficients of $\Delta V_S$ and $Q_0$ (the second and third terms, respectively). So, to avoid from unwanted impact of $K_f$ on $\Delta V_S$ and $Q_0$ (in the second and the third terms of (13)), $K_f$ should be selected the unit. Similarly, $K_V$ (in the second and the third terms of (14)) is assumed to be 1. Then, relationship for the generalized droop control (GDC) can be achieved as follows:

$$\Delta f = \frac{1}{K_f} \left[ \frac{Z}{X} P' - P_0 \right] + K_p K_V \frac{\Delta V_S + K_R Q_0}{K_f}$$

$$\Delta V = \frac{1}{K_V} \left[ \frac{Z}{X} Q' - Q_0 \right] - K_r K_f \frac{\Delta f - K_r P_0}{K_V}$$

(15)

(16)

The block diagram related to (15) and (16) is depicted in Fig. 2.

Fig. 3 shows the conventional block diagram for a VSI. The LCL output filter is also added to prevent from resonance effect in network output. Also, LCL damps the distortion of output sinusoidal waveform and reduces high frequency harmonic resulted from VSI switching. Therefore, it is used in output of inverter to keep appropriate quality for output current and bus-voltage during connection to a weak network. Active and reactive powers pass from low-pass filter as follow:

$$P' = \frac{\omega_c}{s + \omega_c} P$$

$$Q' = \frac{\omega_c}{s + \omega_c} Q$$

(17)

where $\omega_c$ is the cutoff frequency of low-pass filter. The power controller calculates the required active and reactive power and it produces $P'$ and $Q'$ for simultaneous control of voltage and frequency.

The GDC Based on AFSMC

The main weakness point of the GDC method described in previous section is its high dependency to line parameters ($R$ and $X$). This matter results in weak performance of the control method in the case of failure to accurately identify the line parameters. Therefore, a new method based on AFSMC is introduced here to eliminate it. In this method, the GDC block with suggested controller which is shown in Fig. 4 is replaced. Hence, the dependency to line parameters is removed. In other words, the most important factor in the proposed method is the non-dependence on line parameters. Therefore, the proposed method can be used for any DG in a microgrid system without the need to identify the microgrid. In this figure, $e$ parameter which is selected as an input for the suggested controller is defined as follows:

$$e_f = P_0 - P'$$

$$e_q = Q_0 - Q'$$

(18)

(19)

The output of controller ($u$) for $e_f$ and $e_q$ errors are $\Delta f$ and $\Delta V$, respectively.

A. Description of sliding mode

Assume that an interconnected power system can be modeled as follows:

$$\dot{x}(t) = f(x(t)) + Bu(t) + y(t)$$

(20)

where $x(t) \in \mathbb{R}^m$ and $u(t) \in \mathbb{R}^m$ are state and control vectors, $y(t) \in \mathbb{R}^n$ is external disturbance, $\mathbf{B} \in \mathbb{R}^{m \times m}$ is a fixed
The aim of control is to track $x_d$ command through $x$ state using an appropriate control signal. So, we define:

$$e = x - x_d$$  \hspace{1cm} (21)

To design the controller, the first stage is to select a sliding surface defines as follows:

$$s(t) = k_1 e(t) + \int_0^t k_2 e(t) \, dt$$  \hspace{1cm} (22)$$

where $k_1$ and $k_2$ are constants greater than zero.

**B. The AFSMC implementation**

With regards to Fig. 4, it can be written:

$$u = \hat{u}_f + u_{vs}$$  \hspace{1cm} (25)$$

where the control rule ($u^*$) is done through the main tracker controller or the fuzzy controller ($\hat{u}_f$) and the difference among $u^*$ and $\hat{u}_f$ is compensated through the compensator control system ($u_{vs}$). If $\alpha$ is a variable parameter, we will have:

$$u_f(s, \alpha) = \alpha^T \xi$$  \hspace{1cm} (26)$$

where $\xi = [\xi_1, \xi_2, ..., \xi_m]$ and $\alpha = [\alpha_1, \alpha_2, ..., \alpha_m]$ are parameters and regression vectors that $\xi$ is written as follows:

$$\xi = \sum_{i=1}^{m} w_i \alpha_i$$  \hspace{1cm} (27)$$

where $w_i$ is the weight of ith law. Based on [25], it is possible to write an optimal fuzzy control system ($u_f^*(s, \alpha^*)$) for structure proposed in (26) as follows:

$$u_f^*(t) = u_f^*(s, \alpha^*) + \varepsilon = \alpha^T \xi + \varepsilon$$  \hspace{1cm} (28)$$

where $\varepsilon$ shows the error of approximation and it is assumed that it is limited by $|\varepsilon| < \varepsilon$. With applying the considered fuzzy control system to approximate $u^*(t)$, we have:

$$\hat{u}_f(s, \hat{\alpha}) = \hat{\alpha}^T \xi$$  \hspace{1cm} (29)$$

where $\hat{\alpha}$ is approximation vector of $\alpha^*$. With substituting (29) in (30), the following equation is resulted:

$$\dot{x}(t) = f(x(t)) + b[\hat{u}_f + u_{vs}] + \gamma(t)$$  \hspace{1cm} (30)$$

Using (20), (23) and (24), error equation related to the closed loop system can be derived as follows:
\[ k_1 e(t) + k_2 \int_0^t e(t) \, dt + k_3 \dot{e}(t) = \dot{\theta} \left[ \ddot{u}_{ij} + u_{ss} - u \right] = \ddot{z}(t) \]  
(31)

And \( \ddot{u}_{ij} \) will be as follow:

\[ \ddot{u}_{ij} = \ddot{u}_{ij} - e \]

(32)

For simplification, \( \ddot{a} = \ddot{a} - \ddot{a} \) to derive new form of (32) from (28) and (29).

\[ u_{ss} = \ddot{a} \dot{\zeta} e \]

(33)

To make zero \( s(t) \) and \( \dddot{a} \), the Lyapunov function is defined as follows:

\[ V_o(t) = \frac{1}{2} s^2(t) + \frac{B}{2n_1} \dddot{a} \dot{a} \]

(34)

where \( n_1 \) is a positive constant. With differentiation from (34), we have:

\[ V_o(t) = s(t) \ddot{z}(t) + \frac{B}{2n_1} \dddot{a} \dot{a} \]

(35)

\[ = s(t) \dot{\theta} \left( \dddot{u}_{ij} + u_{ss} - u \right) + \frac{B}{2n_1} \dddot{a} \dot{a} \]

\[ = s(t) \dot{\theta} \left( \dddot{u}_{ij} + u_{ss} - u \right) + \frac{B}{2n_1} \dddot{a} \dot{a} \]

(36)

\[ u_{ss} = E \text{sgn}(s(t)) \]

(37)

where \( \text{sgn} \) indicates to the sign function. Then, (35) can be rewritten as follows:

\[ V_o(t) = E \left| s(t) \right| \left| \theta \right| B \leq E \left| s(t) \right| \left| B + \left| s(t) \right| B \right| \]

\[ = -E \left| s(t) \right| B \leq 0 \]

(38)

It means that \( V_o(t) \) is a negative semi-definite function. And,

\[ Q(t) = -E \left| s(t) \right| B \leq V_o(t) \]

(39)

Since \( V_o(t) \) is limited and \( V_o(t) \) is incremental and limited, we have:

\[ \int_0^t Q(t) \, ds(t) \leq V_o(t) \]

(40)

With regard to the rule of Barbalet introduced in [26], the below condition can be followed:

\[ \lim_{t \to \infty} Q(t) = 0 \]

(41)

In other word, \( s(t) \to 0 \) when \( t \to \infty \). Therefore, stability of the proposed AFSMC can be guaranteed.

**Simulation Results**

**A. Standard power system**

In this section, performance of the proposed controller under different conditions of the power system depicted in Fig. 1 is evaluated. Simulation of the considered power system is done to track different values of active and reactive power. If the parameters \( k_1 \) and \( k_2 \) are selected correctly, desirable dynamic of the system including rise time, overshoot and settling time can be obtained easily. In addition, \( n_1 \) and \( E \) are selected to achieve to the best transient response with regard to stability constraint and the control output. The controller parameters required for simulation are summarized in Table 1. It must be added that a separate AFSMC controller is used to control active and reactive power.

<table>
<thead>
<tr>
<th>Controller</th>
<th>( E )</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
<th>( n_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active power controller</td>
<td>12</td>
<td>5000</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Reactive power controller</td>
<td>9</td>
<td>1000</td>
<td>2</td>
<td>9</td>
</tr>
</tbody>
</table>

When changing the reference active power, the generator response for the proposed AFSMC and the discussed SMC controller are obtained and they are compared in Figs. 5 and 6. As it observed in these figures, the speed of the discussed SMC is a little more than the suggested AFSMC but chattering domain in the SMC is about 0.02 pu that is a relative large value. This chattering can affect the power system dynamic, power loss and stability. In contrast, the chattering is so low for the response of microgrid when the suggested AFSMC is applied. In addition, steady-state error for active power in the presence of suggested method is small. In Fig. 6, the frequency of microgrid has been shown for change of active power. It is clear that the performance of the proposed AFSMC controller is much better than the discussed SMC method. In Table 2, dynamic performance of the considered microgrid has been compared for the two controllers. It is observed that the dynamic performance of suggested method is better than the SMC method. Furthermore, THD value in the inverter output voltage is very little in the presence of the suggested method.
Table 2: The dynamic response of different methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Steady-state error [%]</th>
<th>Settling time [s]</th>
<th>Rise time [s]</th>
<th>THD [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMC</td>
<td>1.64</td>
<td>0.01</td>
<td>0.001</td>
<td>0.91</td>
</tr>
<tr>
<td>AFSMC</td>
<td>0.22</td>
<td>0.01</td>
<td>0.005</td>
<td>0.01</td>
</tr>
</tbody>
</table>

For the second case study, it is assumed that the grid voltage is reduced from 1 pu to 0.7 pu in t=0.2s and it is then increased to 1 pu again at t=0.4s. The active power of generator, microgrid frequency, reactive power and bus voltage have been shown in Figs. 7-10, respectively. With regard to Fig. 7, it is observed that there is a significant value of chattering in microgrid response for the discussed SMC controller. As observed in Fig. 8, the change of network frequency is damped faster using the proposed AFSMC controller. It is also illustrated from Figs. 8 and 9 that the reference active power and reactive power are well tracked by the microgrid. It is clear from Fig. 10 that the bus voltage response of microgrid has significant overshoot for the SMC while there is a satisfactory dynamic response for the suggested AFSMC controller.

B. The four-bus four-DG microgrid

To demonstrate the effectiveness of the suggested secondary controller, a 380 V, 50 Hz four-bus four-inverter-based DG islanded microgrid shown in Fig. 11 is used. All loads and lines are modeled as series RL branches.
follows:
1. The proposed secondary control is activated at t=1.5s.
2) Load #1 is increased at t=2s.
3) Load #3 is disconnected at t=3s.
4) Switch S in Fig. 11 is opened at t=3.5s.

In order to show the effective performance of the proposed secondary control, following the process of islanding at t=0s, the proposed secondary control is deliberately disabled. Fig. 12 shows the response of the microgrid such as voltage, frequency, active power and reactive power to the aforementioned fault. As seen in this figure, the terminal voltage of the DGs and the frequency of the microgrid deviate from their nominal values by their droop controller. Hence, the secondary control loop should restore the frequency and voltage of the microgrid. After the activation of the proposed secondary loop controller (i.e. AFSMC) at t=1.5s, the microgrid’s voltage and frequency are quickly restored to the nominal values as seen in Figs. 12 (a) and (b). When load#1 is increased at t=2s, the proposed controller shows good tracking and robust performance against the increase of load#1 and exactly restores the voltage and frequency of the microgrid. To highlight the robust performance of the proposed secondary controller, it is assumed load #3 is removed at t=3s. It is clear from Fig. 12 that the suggested secondary controller can restore the microgrid’s the voltage and frequency rapidly.

Next, the performance of the proposed controller is evaluated under disconnecting and reconnecting of DGs. For this purpose, DG#4 is disconnected at t=2s and reconnected at t=2.5s. Fig. 13 depicts the response of the microgrid to this fault. After disconnecting DG#4 from the microgrid, the remaining DGs increase power generation to return the amount of power to the generated power before disconnecting. Therefore, the power generation of the remaining DGs increases, while the power generated by DG#4 drops to zero during disconnecting as shown in Fig. 13.c. Besides, at t=2.5s, the process of the synchronization is activated and DG#4 is reconnected to the microgrid. In spite of disconnecting and reconnecting of DG#4 (except for the transient state), AFSMC can also control accurately the voltage and frequency before, during, and after disconnecting and reconnecting as seen from Fig. 13. Here, a comparative study is conducted between the proposed AFSMC and the secondary control loop proposed in [27]. It should be noted that the controller proposed in [27] is an asymptotic controller that ensure the global asymptotic stability of the microgrid. Fig. 14 displays the simulation results for when voltage and the frequency of DG#1 are restored using the two controllers.

Fig. 12: The response of the microgrid to a multiple fault, (a) terminal voltage of DGs; (b) Frequency of DGs; (c) Active power of DGs; (d) Reactive power DGs

Fig. 13: The response of the microgrid to the disconnecting and reconnecting of DG#4, (a) terminal voltage of DGs; (b) Frequency of DGs; (c) Active power of DGs; (d) Reactive power DGs.
For simplicity, only the frequency response and voltage of the one of DGs are indicated. The results can be concluded: 1) compared to the proposed method in [27], our proposed method quickly reaches to the nominal value and it shows more accurate performance for activating the controller, the reconfiguration of the structure and load variations, 2) the proposed method provides better disturbance rejection properties in the reconfiguration and load variations.

Conclusion

A solution for droop control based on generalized droop control was introduced to regulate simultaneously voltage and frequency in islanded microgrid. A generalized droop control method based on conventional voltage and frequency droop control was presented first but it was shown that this method depends seriously on power system configuration and transmission line parameters. To solve the problem, an independent generalized droop control method was suggested that was independent from the model of the microgrid. The suggested controller simulates the dynamic behavior of the generalized droop control. In this suggested intelligent controller, the abilities of the sliding mode controller and fuzzy controller are combined to introduce an appropriate adaptive controller. In order to ensure the stability of the closed loop system, an effective algorithm based on the Lyapunov stability rule was also established. To reduce the chattering phenomenon, a compensatory controller was used for the suggested controller. This proposed controller was applied to a typical microgrid for control of voltage and frequency. The simulation results showed great ability of the suggested controller to keep microgrid stability in various conditions.

Fig. 14: The comparative study results.

Author Contributions

The idea of the work was proposed by E. Limouchi, S. A. Taher, and B. Ganji. The simulation model was developed by E. Limouchi and he also carried out the data analysis. S. A. Taher, and B. Ganji interpreted the results and wrote the manuscript.

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Conflict Of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the
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authors.

Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$f_m$</td>
<td>Measured frequency</td>
</tr>
<tr>
<td>$f_{set}$</td>
<td>Standard grid frequency set point</td>
</tr>
<tr>
<td>$P$</td>
<td>Active power output</td>
</tr>
<tr>
<td>$P_o$</td>
<td>Active power set value</td>
</tr>
<tr>
<td>$V_{abc}$</td>
<td>Three-phase voltage</td>
</tr>
<tr>
<td>$V_o, V_v$</td>
<td>Clark voltage</td>
</tr>
<tr>
<td>$I_{abc}$</td>
<td>Three-phase current</td>
</tr>
<tr>
<td>$V_{o}, V_q$</td>
<td>Park voltage</td>
</tr>
<tr>
<td>$Q_o$</td>
<td>Reactive power set value of the generator</td>
</tr>
<tr>
<td>$Q$</td>
<td>Reactive power output</td>
</tr>
<tr>
<td>$K_v$</td>
<td>Voltage droop setting</td>
</tr>
<tr>
<td>$K_f$</td>
<td>Frequency droop setting</td>
</tr>
<tr>
<td>$V$</td>
<td>Voltage of coupling point</td>
</tr>
</tbody>
</table>

References


Biographies

Ehsan Limouchi was born in Esfahan, Iran, in 1980. He received the M.Sc. degree in Electrical- Control Engineering from Islamic Azad University, Science and Research Branch, Tehran, Iran in 2007. He is currently working toward the Ph.D. degree in Electrical Engineering at University of Kashan. His research interest includes control theory, power electronics and micro grid control systems.
Seyed Abbas Taher (SM’17) was born in Kashan, Iran, in 1964. He received the B.Sc. degree in electrical engineering from the Amirkabir University of Technology, Tehran, Iran, in 1988, and the M.Sc. and Ph.D. degrees in electrical engineering from Tarbiat Modares University, Tehran, in 1991 and 1997, respectively. In 1996, he joined the Faculty of Engineering, University of Kashan, where he has been a Full Professor since 2016. His current research interests include power system optimization and control design, analysis of electrical machines, power quality, and renewable energy.

Babak Ganji was born in Isfahan, Iran, in 1977. He received B.Sc. degree from Isfahan University of Technology, Iran in 2000, and M.Sc. and Ph.D. from University of Tehran, Iran in 2002 and 2009 respectively, all in major electrical engineering-power. He was granted DAAD scholarship in 2006 from Germany and worked in institute of power electronics and electrical drives at RWTH Aachen University as a visiting researcher for 6 months. He has been working at University of Kashan in Iran since 2009 and his research interest is modeling and design of electric machines especially switched reluctance motor.

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