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# A method to synchronize single-phase floating with grid without high voltage measurement or high bandwidth communication

Zhihui Yuan, *Student Member, IEEE,* Sjoerd W.H. de Haan, *Member, IEEE,* Braham Ferreira, *Fellow, IEEE,*

***Abstract*—Most of FACTS devices and grid connected converters need the information about the frequency and phase of the grid for synchronization and control. In some cases, the value to be measured that is used as synchronization signal is at remote bus or at a different voltage potential, which would require expensive high voltage measurements or high bandwidth communication. A new synchronization method for single-phase floating convertert is presented, which neither requires high voltage measurements nor high bandwidth communication. The method is applied to a new FACTS device - Distributed Power Flow Controller (DPFC) which is derived from the UPFC. Within the DPFC, multiple single-phase converters are distributed along the transmission line instead of one big 3-phase converter. The principle of this method is to use the line current as the rotation reference frame which enables the series converter to read the phase and frequency information locally. In this case, only the signals in dc quantity are communicated, and the system stability during communication failure is greatly improved.**

***Index Terms*—Synchronization, power converters, phase locked loops, load flow control, FACTS, power quality.**

## I. INTRODUCTION

In recent decade, the number of grid connected converters increases greatly because of distributed generation, electricity marketing, etc [1], [2]. Since there is no mechanical rotation in these active converters, it is the most important issue for grid connected converters to capture the frequency and phase information from the grid and generate the rotation virtually for synchronization. FACTS device is a part of grid connected converter and aimed to control the parameters of networks. In some cases, FACTS devices are controlled remotely, and the synchronization signal is transferred through communications, as shown in Fig.1. As there is delay of the sync signal transfer and the delays may be different between each FACTS device, it causes a problem to synchronize the FACTS devices.

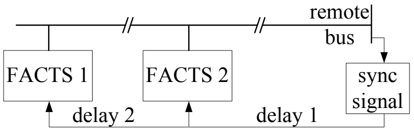

Fig. 1. Synchronizing FACTS devices by remote control; the delays may cause synchronization error

The synchronization of single-phase floating converters is studied in this paper, because it is difficult to get the line-to-line voltage information locally, which is used for grid synchronization. As the Distributed Power Flow Controller (DPFC) recently presented in [3] contains a large number of single-phase floating converters, it is used as a study case. The DPFC is derived from the UPFC and has the same capability of simultaneously adjusting all the parameters of the power system: line impedance, transmission angle, and bus voltage magnitude [4]. Within the DPFC, the common dc link between the shunt and series converters is eliminated, which provides flexibility for independent placement of series and shunt converter, see Fig.2. The DPFC uses the transmission line to exchange active power between converters at the 3rd harmonic frequency [3]. Instead of one large three-phase converter, the DPFC employs multiple single-phase converters (D-FACTS concept [5]) as the series compensator.

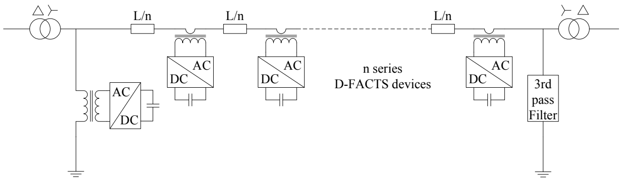

Fig. 2. Distributed power flow controller

For the DPFC control, the series converters, which are floating with respect no ground, need the line-to-line voltage of the line. This measured line-to-line voltage is used to synchronize the converter with the network. This voltage is important for the DPFC, because it is the base of the rotation reference frame of the vector control [6], which provides the frequency and phase information. To achieve phase voltage information, high voltage measurements could be used for every converter, however this is costly, since the number of series converters is large and the converters are distributed along the transmission line. The voltage can also be measured at the substation, and together with the control signals, transmitted to the series converters through communications. Because the transmitted information concerns ac quantities, high bandwidth communication would be needed. With this method, the converters will lose synchronization, when the communication has a failure. Therefore, it is important to find a new synchronization method which does not require high voltage measurement and provide a higher reliability during communication failure.

This paper presents a new method, which particularly solves the problem to synchronize the single-phase floating converter with the power system, which does not require high voltage measurement or high bandwidth communication. The new method is based on the dq-transformation, and sending dc

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quantities instead of ac quantities.

## II. PRINCIPLE OF THE NEW SYNCHRONIZATION METHOD

The principle of the new synchronization method for the single-phase floating converter is to use the line current as the sync-signal and remotely control floating converters by transferring control signal in dc quantity, see in Fig.3.

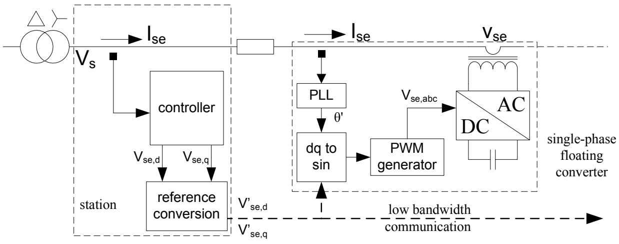


Fig. 3. Block diagram with the new synchronization method

To eliminate the high voltage measurement of the single-phase floating converter, the converters should be remote controlled. As in a station or substation all the information of the system is available, the controller for the floating converters can be placed there and generates control signals for the floating converters without extra cost. These control signals are transmitted to the converters remotely through power line communication or wireless communication. In this case, the control signals generated by the controllers are ac quantities; therefore a high bandwidth communication is required. Because of the delay and disturbance of the communication, it is difficult to ensure that all the floating converters received the ac control signals correctly.

To minimize the effect of the communication delay and disturbance, the communicated ac quantities are transformed into dc quantities by the Park Transformation [7]. To avoid of ac quantity communication, the line current is used as the rotation reference frame, instead of the line-to-line voltage which is used in common. The line current can be easily captured by the series converter locally without extra cost. The Single-phase Phase Lock Loop (PLL) [8], [9] is employed in each single-phase floating converter to achieve the phase and frequency information of the grid. In this case, only the $d$ and $q$ information that is in dc quantity is transmitted to the converters. Together with the phase and frequency information from the line current, the signals in dc quantities can be transformed back into ac by the inverse Park-transformation.

Conventionally, the reference voltage for the converters controller $v_{se}$, which is generated by the controller, uses the bus voltage $v_s$ as the rotation reference frame. As in this new method, the line current $i_{se}$ is used as the rotation reference frame; a rotation reference frame conversion is required in order to achieve the same control result. The objective of this rotation reference frame conversion is to keep the ac voltage injected by the floating converter the same as the voltage generated by the controller. Consequently, the rotation reference frame conversion is given by:

$$\begin{aligned}[V'_{se,dq}] &= T_{dq}(\theta_{I_{se}})][V_{se,abc}] \\ &= [T_{dq}(\theta_{I_{se}})][T_{dq}(\theta_{v_s})]^{-1}[V_{se,dq}] \end{aligned} \tag{1}$$

where $[V'_{se,dq}]$ $[V_{se,dq}]$ are the series voltage in $i_{se}$ and $v_s$ rotation reference frame respectively, and $[T_{dq}(\theta_{I_{se}})]$ $[T_{dq}(\theta_{v_s})]$ are corresponding Park Transformation matrix. The phasor diagram of the rotation reference frame conversion is illustrated in Fig.4.

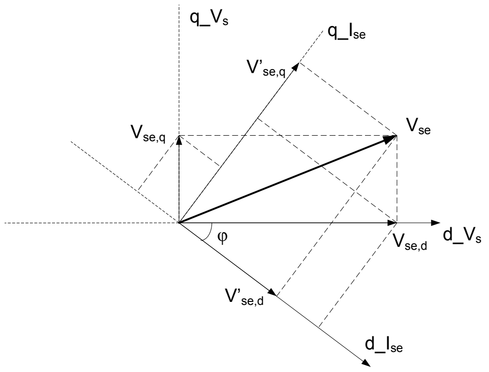


Fig. 4. Phasor diagram of the rotation reference frame conversion

The angle $\varphi$ between the voltage $v_s$ and current $i_{se}$ can be measured at the station, accordingly the rotation reference frame can be written as:

$$\begin{aligned} V'_{se,d} &= V_{se,d}\cos\varphi + V_{se,q}\sin\varphi \\ V'_{se,q} &= -V_{se,d}\sin\varphi + V_{se,q}\cos\varphi \end{aligned} \tag{2}$$

Concerning the communication, this synchronization method is greatly increased the reliability of the system. A buffer can be used to store the received data. During communication failures, the last received information can be used, together with the phase and frequency information from the line current, the floating converter will still keep synchronization.

## III. ANALYSIS

In the conventional method, it is instantaneous to transform the $dq$-components into $abc$-frame. Comparing with the conventional method, the new method requires single-phase PLL to capture the phase information from the line current. Since the PLL has delay and the line current varies during the adjustment of the floating converters, it is important to find the performance of this new method to the network. Fig.5 shows the simplified transmission line with the floating converter with the new synchronization method.

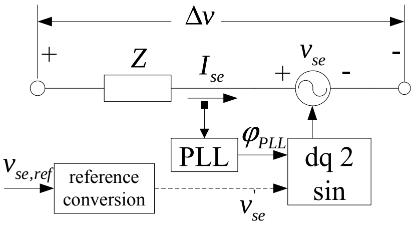


Fig. 5. Simplified transmission line with the floating converter with the new synchronization method

The voltage across the line is $\Delta v$, the impedance of the line is $Z = R + jL$, and the current through the line is $i_{se}$.

With the voltage $v_{se}$ injected by the converter, the relationship between the current and voltages is given by:

$$\Delta v - v_{se} = Zi_{se} \tag{3}$$

Assuming that the angle of the current is $\varphi$ and the angle captured by the PLL is $\varphi_{PLL}$, then voltage injected by the series converter is:

$$\begin{aligned} v_{se} &= v'_{se} \cdot 1\angle\varphi_{PLL} = \frac{v_{se,ref}}{1\angle\varphi} \cdot 1\angle\varphi_{PLL} \\ &= v_{se,ref} \cdot 1\angle\varphi_{PLL} - \varphi \end{aligned} \tag{4}$$

As shown in (4), the single-phase PLL plays a important role in this new method. In order to evaluate this new synchronization method, the PLL should be studied first. The topology of the PLL employed in the series converter is shown in Fig.6.

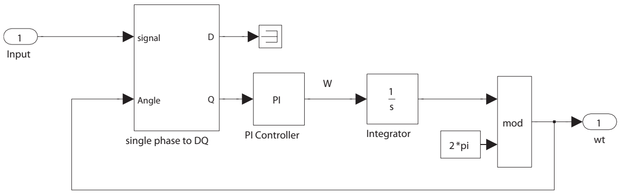


Fig. 6. Topology of the employed single-phase PLL

The principle of the PLL is to use PI controller to force the PLL rotation frame to approach the input signal. When the $q$ component of the PLL is zero, the PLL frame is locked with input signal. The single-phase $dq$-transformation uses the delay method [10], because it is easy to be implanted in the floating converter. Assuming the network frequency $\omega$ does not change, the $q$ component inside the single-phase PLL is given by:

$$\begin{aligned} x_q^{PLL} &= \sin(\omega t + \varphi)\cos(\omega t + \varphi_{PLL}) \\ &\quad + \sin[\omega(t - {}^{T}\!/_{4}) + \varphi]\sin(\omega t + \varphi_{PLL}) \\ &= \sin(\varphi - \varphi_{PLL}) \end{aligned} \tag{5}$$

Consequently, the single-phase PLL can be represented by:

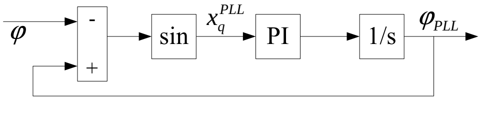


Fig. 7. Single-phase PLL representation

As the difference between $\varphi$ and $\varphi_{PLL}$ is small, their subtraction is around zero. So the sinusoid function in the PLL can be linearized as $\sin x \approx x$. Consequently, the open-loop transfer-function between $\varphi$ and $\varphi_{PLL}$ can be written as:

$$G(s) = \left(\frac{K_i}{s} + K_p\right)\frac{1}{s} = \frac{K_i + sK_p}{s^2} \tag{6}$$

and the close-loop transfer function is:

$$\frac{\varphi_{PLL}}{\varphi} = \frac{G(s)}{1 + G(s)} = \frac{sK_P + K_i}{s^2 + sK_P + K_i} \tag{7}$$

Substituting (7) to (4), the voltage injected by the series converter can be written as:

$$v_{se} = v_{se,ref} \cdot 1\angle\varphi\left(\frac{-s^2}{s^2 + sK_P + K_i}\right) \tag{8}$$

As shown in (8), the voltage $v_{se}$ and its reference have the same value in steady-state. However, there is a phase difference between them during the transient, and the transient depends on the parameters of the PLL.

## IV. CASE STUDY: THE NEW SYNCHRONIZATION METHOD UTILIZED IN THE DPFC

As the DPFC employ a large number of single-phase floating converters as the series converters and the series converters can injects $360°$ voltage, the DPFC is study case to demonstrate this new synchronization method.

### A. Introduction of the DPFC

Multiple individual converters cooperate together and compose the DPFC, see Fig.2. The converters connected in series to the transmission lines are the series converters. They can inject a $360°$ controllable voltage at the fundamental frequency; consequently they control the power flow through the line. The converter connected between the line and ground is the shunt converter. The function of the shunt converter is to compensate reactive power to the grid, and to supply the active power required by the series converter. In a normal UPFC, there is active power exchange through the DC link that connects the series converter with the shunt converter.

Since there is no common dc link between the shunt and series converters in the DPFC, the active power is exchanged by harmonics and through the ac network. The principle is based on the definition of active power, which is the mean value of the product of voltage and current, where the voltage and current comprise fundamental and harmonics. Since the integrals of all the cross-product of terms with different frequencies are zero, the time average active power can be expressed by:

$$P = \sum_{n=1}^{\infty} V_n I_n \cos\phi_n \tag{9}$$

where $n$ is the order of the harmonic frequency and $\phi_n$ is the angle between the current and voltage of the nth harmonic. Equation 9 describes that active powers at different frequencies are isolated from each other and that voltage or current in one frequency has no influence on other frequency components. The 3rd harmonic is chosen here to exchange the active power, because it can easily be filtered by Y-$\Delta$ transformers.

### B. DPFC primary control

The shunt converter injects a constant 3rd harmonic current into the transmission line, which is intended to supply active power for the series converters. The shunt converter extracts some active power from the grid at the fundamental frequency to maintain its dc voltage. The dc voltage of the shunt converter is controlled by the d component of the current at the fundamental frequency, and the q component is utilized for reactive power compensation. The series converters generate a 360° rotatable voltage at fundamental frequency, and use the voltage at the 3rd frequency to absorb active power to maintain their dc voltages. The block diagram of the DPFC and its control is shown in Fig.8.

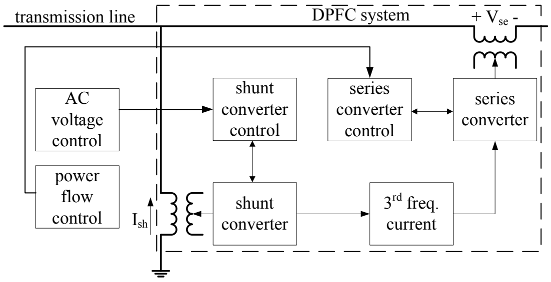


Fig. 8. Block diagram of the control of a DPFC

## C. Applying the new synchronization method to the DPFC

The control signals generated by the power flow control block at the shunt converter are transferred to every series converter. By using the conventional method, the control signals in ac quantity are transmitted. As the series converters are distributed along the line, the distances between each series converter and the shunt converter are different. Therefore, the communication delays for every series converter is unique, which leads to the difficulty of the series converters synchronization.

By applying the new synchronization method to the DPFC, a rotation reference conversion block is added behind the power flow control and each series converter is equipped with single-phase PLL, see in Fig.9. In this case, the series converter gets the synchronization signal locally, and the communication delay will not lead to any synchronization problem.

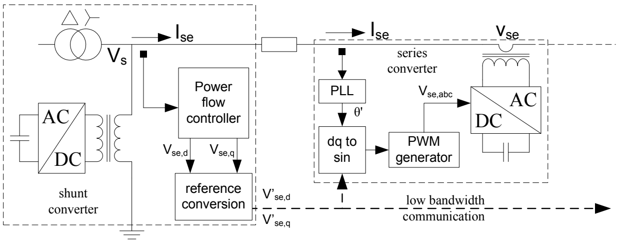


Fig. 9. DPFC block diagram with the new synchronization method

## V. SIMULATION OF THE DPFC WITH THE NEW SYNCHRONIZATION METHOD

The new synchronization method has been simulated in Matlab, Simulink. The system shown in Fig.10 is used as a test example. The magnitudes of the voltages at grid is 1pu, and $v_s$ leads $v_r$ 30°. The transmission line is represented by a 0.5pu inductor, and the resistance is neglected. To evaluate the new synchronization method, two cases are simulated. Case 1: testing the transient behavior of the new method; case 2: demonstrate the reliability during the communication failure.

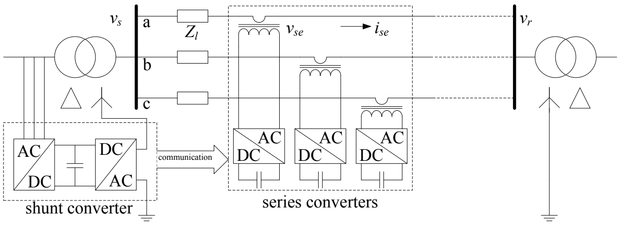


Fig. 10. The DPFC simulation circuit

To test the transient of the new method, the step response is demonstrated. A step change of the reference for the voltage injected by the series converter is made at the moment t=2s. To have a clear view, the voltages in ac quantity are transformed into dq-frame by the Park Transformation, and their rotation reference frame is $v_s$ . The injected voltage by using the new synchronization method in dq-formation is shown in Fig.11.

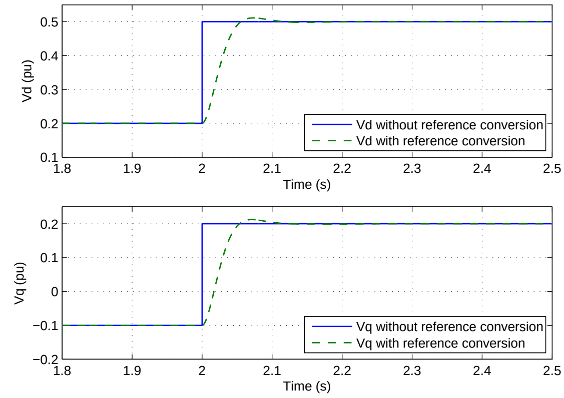
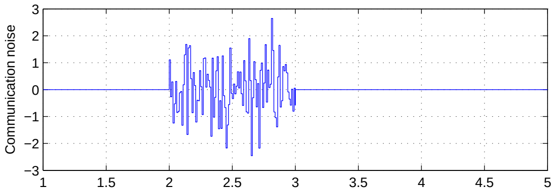


Fig. 11. Comparison between the step responses of the converter with and without reference conversion

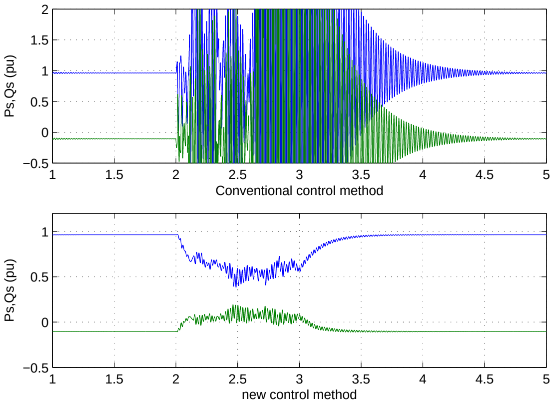
As shown, with or without the reference conversion, the series voltages have the same value in steady-state. By using the line current as the rotation reference frame, there is a delay between the reference signal and real voltage injected by the converter. This delay depends on the performance of the single-phase PLL, and around 0.1s in this simulation.

To demonstrate the improvement of the system reliability during the commutation failure, a large noise shown in Fig.12(a) is added between 2s to 3s. The power flow through the line and the dc voltage of the series converter are shown in Fig.12(b) & 12(c).

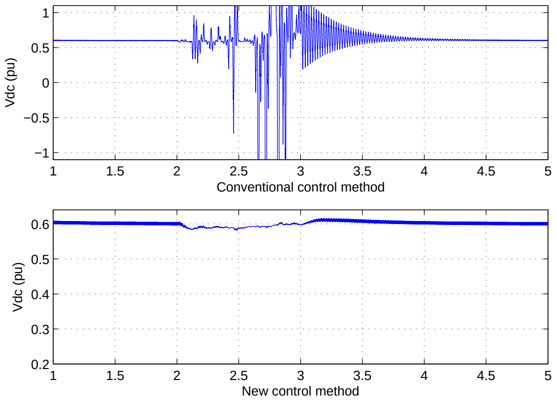


(a) The communication noise

As shown, in the normal operation, the conventional and the new synchronization method have the same control results. During the communication failure, by using the conventional synchronization method, the system totally loses the stability.



(b) Power flow through the line for both synchronization methods



(c) The DC voltage the series converter for both methods

Fig. 12. Comparison of the synchronization method during the communication failure

While by using the new method, the series converters do not lose the synchronization with grid, and the dc capacitor voltage is well maintained. After the failure, the system recovers much faster by using the new method.

## VI. CONCLUSION

This paper presented a new synchronization method, which can be used for single-phase floating converters which are grid connected. This method is based on the $dq$-transformation. The line current is used as the rotation reference frame, and only the $dq$ component, which is in dc quantity, is transmitted. By using this method, there is no requirement for high voltage measurement at each converters. Low bandwidth communication is employed in this method, since only dc signals are communicated. The system reliability is greatly increased during communication failures, because the converter can keep the control capability by using last received data and the rotation reference frame from the current.

## ACKNOWLEDGEMENT

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**Zhihui Yuan** was born in Hei Long Jiang, China, 1981. He graduated from Harbin Institute of Technology at 2004, and received bachelor degree in electrical engineering. He got his master degree in Electrical Power Engineering at the Chalmers Technology University, Sweden, 2005. From July to December 2005, he did his master final thesis at ETH Zurich. Since April 2006 till now, he was working on a PhD project ’Active power flow control in utility grid’ in Electrical Energy Conversion (EEC) group, TU Delft, the Netherlands.

**S.W.H. de Haan** was born in Apeldoorn, The Netherlands in 1948.He received his M.Sc degree in Physics from the Delft University of Technology, Delft, the Netherlands in 1975. After his graduation he was employed by TPD-TNO (applied physics research center) in the field of heat transfer. In 1976 he became a member of the scientific staff of the power electronics laboratory at the Delft University and later as assistant/associate professor at the Eindhoven University of Technology. From 1993 until 1995 he was senior researcher with ECN (The Netherlands Energy Research Foundation) in Petten, where he was in charge of research on electrical conversion systems for renewable energy systems, in particular wind energy and photovoltaic energy. In 1995 he again joined the Delft University of Technology as associate professor in Power Electronics. His research interest is currently mainly directed to Power Quality Conditioning, i.e. the development of power electronic systems for the conditioning of the power quality in the public electricity network. Specific projects concern the development of an electronic tap changer for 10 kV distribution transformers, active filters for the elimination of specific harmonics and pulse width modulated rectifiers for asymmetrical grids.

**Jan Abraham Ferreira** was born in Pretoria, South Africa, and received the B.Sc.Eng.(cum laude), M.Sc..Eng.(cum laude), and Ph.D. degrees in Electrical Engineering from the Rand Afrikaans University, Johannesburg, South Africa. In 1981 he did research on battery vehicles at the Institute of Power Electronics and Electric Drives, Technical University of Aachen, and worked in industry as a systems engineer at ESD (Pty) Ltd from 1982-1985. From 1986 until 1997 he was at the Faculty of Engineering, Rand Afrikaans University, where he held the Carl and Emily Fuchs Chair of Power Electronics in later years. In 1998 he became professor of Power Electronics and Electrical machines at the Delft University of Technology in The Netherlands, and since 2006 he is the head of the department Electrical Sustainable Energy at the same university.

Dr. Ferreira is a fellow of the IEEE. During 1993-4 he was chairman of the South African Section of the IEEE. He is the founding chairman of the IEEE Joint IAS/PELS Benelux chapter. He served in 1995-6 as the chairman of the IEEE IAS Power Electronic Devices and Components committee. Currently he is an associate editor of the PELS Transactions and the treasurer of the IEEE PELS.

Dr. Ferreira served as chairman of the CIGRE SC14 national committee of the Netherlands from 1999-2002 and is a member of the executive committee of the European Power Electronic Association EPE Society (1999-2003; 2008 - present).