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Optimising Active Power Losses

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A Transmission System Friendly Micro-grid: Optimising Active Power Losses

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Abstract— **Looking to the future, there are several challenges that electricity networks will face: prosperity, global sustainable growth and security. The electricity industry situation is complex because resources worldwide are becoming scarce and the need for sustainable growth is important. Dealing with this challenge led to the foundation of micro-grids. The classical "micro-grid" defines a mix of distributed energy resources (DER) capable of providing sufficient and continuous energy to a significant portion of the internal demand. Transmission system friendly micro-grids is a novel concept to encourage the power electronic converters to provide grid services and functionalities in line with new standards such as IEEE 1547-2018. This paper presents a method for reducing losses by injecting reactive power from the grid-connected DER. The methodology is developed in Python and the system is modelled in DIgSILENT PowerFactory. The paper includes numerical results of the proposed methodology to show the suitability of the proposed concept.**

Index Terms−**Grid optimisation, power losses minimization, smart converters, volt-var control.**

I. Introduction

The classical concept of *micro-grid* (μg) defines it as a set of interconnected distributed energy resources (DER) capable of providing enough and continuous energy to a significant portion of the internal demand [1]. The μg has been intensively developed during the last decade, as an alternative mechanism to support the main supplying grid and provide grid resilience [2]. The concept of μg is not new, the first attempt to define it can be found on CERTS micro-grid White Paper (2001), created by Robert Lasseter [3]. That white paper recognised the significant potential of smaller DER (< 100 kW/unit) to meet customer's and utility's needs; the report recognises the μg as an organised set of DERs. The modern concept of grid-friendly or smart converter opens the door to more active interactions between μgs, distribution system and transmission systems. Some efforts on active power loss reduction in distribution grids have been based on the use of battery systems [4]. However, modern power electronic converters, as those, are also installed in photovoltaic systems, electric vehicles, etc.

The objective of this paper is to present a novel approach of active power losses minimisation in distribution systems by injecting reactive power directly into the grid from smart converters. The optimisation process includes minimisation of the active power losses by enabling the appropriate setting of the reactive power output of the DER as well as the tap settings of the transformers connected. Also, this paper presents numerical results of the proposed control methodology applied to a test system; the methodology is implemented using Python for global control/calculations and power system simulations using DIgSILENT® PowerFactory™. Simulations results demonstrate the suitability of the proposed transmission system friendly micro-grid.

II. General Background

A. The concept of the μg

The concept of μg has evolved over time and has been adapted to specific interests and locations. The European vision of μg and its applicability are found in many EU research projects [5]–[7]. The European concept of a μg includes the penetration of DER (e.g. microturbines, fuel cells, PV, etc.) in LV distribution systems together with storage devices (e.g. flywheels, energy capacitors and batteries) and flexible loads. The μg can be operated in a non-autonomous way if interconnected to the grid, or in an autonomous way if disconnected from the main grid. The operation of micro-sources in the network can provide distinct benefits to the overall system performance if managed and coordinated efficiently. Modern μgs can be found as a purely direct current (DC), alternating current (AC), or hybrid schemes AC/DC.

B. A cluster of Micro-Sources and Loads

A μg is defined as a cluster of micro sources and loads operating as a single controllable system that provides power with its local area. With the light provided by the dawn of *smart grids* (SGs) together with the high penetration of cybernetical systems in the μgs, the μg might be characterised as the "building blocks of smart grids" [8], [9], they are a very promising, novel network structure. The μgs typically include several DER technologies such as the

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case of solar PV (which outputs DC power) or microturbines (high-frequency AC power), those technologies require power electronic converters to as interfaces to the grid. It is typical to find *power electronic converter* (PEC) as interfaces, like DC/AC or DC/AC/DC converters, to connect the main source to the main power grid.

C. Power Electronic Interfaces

The *power electronic interfaces* (PEI) provide an excellent mechanism to enable controllability features to the micro-sources; especially considering the technological advances reached by the development of the smart grids. The power inverter, or simply inverter, is a frequently used power electronic converter used in the micro-sources to provide interfacing between DC and AC. The power inverters can play an important role in the micro-grid control when multi-layered management systems are implemented. The power inverter plays a critical role in frequency and voltage control in islanded µgs, and in facilitating participation in black start strategies. µgs feature special control requirements and strategies to perform local balancing and to maximise their economic benefit.

III. µG CONTROLLER

The new IEEE Standard 1547-2018 [10], an IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, overcomes the limitations of low penetrations of power converter based DER in the electrical system [10], and adds advanced features on DER, like smart features to solar PV inverters. *Smart solar photovoltaic inverters* features include voltage and frequency ride through, voltage and frequency support as well as ramp rates [11]. Standards are a key enabler for the deployment of µgs and the associated DER within them. The IEEE Standard 1547-2018 [10] created a new tendency in the PEC industry, the so-called "*smart inverter*". The IEEE standard defines many features that should be included in a power inverter in order to be named smart, especially the digital architecture, bidirectional communications capability and robust software infrastructure.

A. Modern µg Controls

Modern µg controls must deliver special functional features [10]: (i) Integrity to represent the µg to the utility grid (see Figure 1) as a single self-controlled entity in a way that provides frequency control like a classical synchronous generator. (ii) Control the active power flow (P_{ij}) in the µg in order to avoid power flow exceeding cable/line ratings ($I_{ij}^{nominal}$). (iii) Control capability to regulate voltage (V) and frequency (f) within acceptable power quality bounds during islanding operation and dispatch resources to maintain energy balance. (iv) Provide mechanisms to safely reconnect and resynchronize the µg with the main grid, when required.

B. Implementing a Standard

There are abundant benefits of implementing a standard for micro-grid controllers. The successfully created standards can facilitate the deployment and adoption of micro-grid concepts by the utility industry; they can reduce system integration costs, help resolve in-the-field interoperability issues to reduce time to deployment, and lower technical barriers to advanced applications for micro-grids. A µg is basically a group of interconnected loads and DERs within a clearly defined electrical boundary that must act as a single controllable entity concerning the utility grid and able to operate in both grid-connected or islanded mode. In this paper, only the grid-connected operational mode is considered.

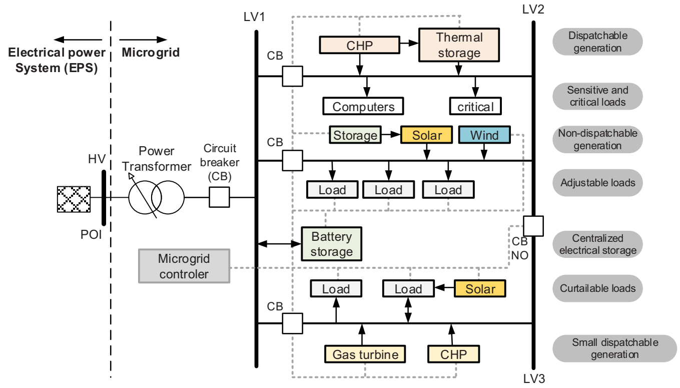

Figure 1. Diagram showing the structure of a µg and its components. Taken from [11] and the model has been modified for the very specific purpose of this paper.

Figure 1 shows a basic schematic diagram of a representative structure of a µg as considered in this paper. The boundary between the utility grid (distribution system) and the µg is defined by the high-voltage-side of the step-down transformer and indicated as the connection to the distribution grid at the *point of interconnection* (POI). The POI is a very important point in the µg because it is the place where all the interactions with the utility grid take place [10], [12], [13], [14]. There are many topologies on the design of a µg, and it is possible to have multiple connections including an alternate grid utility connection at the substation [15]. However, a µg will only have one connection with the utility grid which will be closed at a given time [16]. A very detailed discussion of micro-grid planning, designing, and operating the micro-grid is given in IEEE Standard 1547.4 [17]. However, this standard does not address issues related to the power exchanges between the µg and the utility grid.

The modern IEEE Std. 2030.7, IEEE Standard for the Specification of Micro-grid Controllers [18] is a key document on defining the operation and control of the micro-grid as it introduces the key concept of the *Micro-grid Energy Management System* (MEMS). Also, this standard includes the specifications of the control functions that define the µg as a system that can manage itself and operate autonomously or grid-connected, and seamlessly connect to the utility grid, and enable the micro-grid to be disconnected from the utility grid to exchange of power and the supply of ancillary services.

The controllability of the micro-grid is increasing and the potential value to provide support to the *Distribution System Operators* (DSO) is a real option, especially enhancing the operation and increasing the resilience. Today, the digitalisation of the power systems is creating a clear path to overcome barriers and allow a very active and dynamic interaction between *Transmission System Operators* (TSO) and DSO. One of these trends is the increasing volume of *distributed generation* (DG) being connected to the distribution grid and more important, enhancing the services offered by them. The active distribution network is a reality and the potential of unfolding a massive synergy from DSO services to support TSO. Interactions between TSO-DSO have the potential to help on minimising many power systems problems [14]: (i) Relieving congestion of Transmission-Distribution interface (potential to defer infrastructure investment). (ii) Relief of congestion of transmission lines and distribution lines. (iii) Fully managed voltage support (TSO ↔ DSO). (iv) Balancing challenge. (v) Anti-Islanding, re-synchronization & black-start. (vi) Coordinated protection.

There are many demonstratives projects on possible architectures for optimised interaction between TSOs and DSOs, [18] shows a summary of the demonstration project focused on the coordinated provision of power balancing, congestion management and voltage regulation.

IV. The Concept: Transmission System Friendly micro-Grid

A traditional power system uses transformers equipped with *on load tap changer* (OLTC) to keep control HV voltage level by the means of EHV/HV while the EHV level is managed through a classical Volt-var control (shunt capacitors/reactors, transformer tap changers, synchronous generators, synchronous condensers, FACTS e.g. STATCOM, SVC; and HVDC) (see Figure 2).

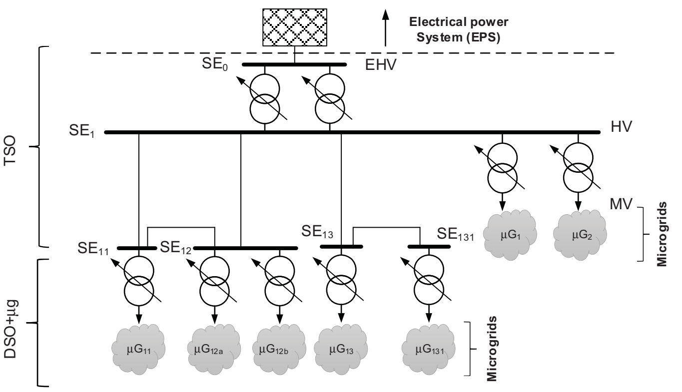

Figure 2. The general scheme of an EHV/HV/MV+μg system. TSO-DSO boundaries are shown.

The effectivity of the reactive power (Q) control actions to control voltages (V_i) in power systems is well-document in the literature [19], in fact, the influence of the reactive power from MV networks on the HV voltage is roughly proportional to the short-circuit power of the substation *short-circuit current* (SCC).

The technological advances on DER technologies and their interface to the grid are making PEC based DER a very attractive solution to provide Volt-var control and positively impact the distribution systems. Modern inverter interfaced DER has the potential to improve customer load voltage, voltage regulation, voltage flicker and other related issues.

V. Methodology

In this section, a methodology to minimise the total active power loses (P_{losses}) in a TSO+DSO+μg system is presented. In order to minimise the power loses, the DER is assumed to have PEC enabled with smart converter functionalities and the step-down transformer is enabled with OLTC.

The core of the methodology is an optimisation designed to set up the reactive power injections ($Q_{i\mathrm{DER}}$, $i = 1, \ldots, n_{DER}$) of the DER as well as the tap settings of the transformers connected (TAP_i, i = 1, …, n_{TAP}) to the network so that the system active power losses are minimised while keeping the voltage inside a power quality range. The proposed methodology is developed to perform the minimisation of the active power losses for each time period during the time horizon of a single day (later in this paper the methodology is demonstrated using 30-mins resolution over 24 hours).

In this paper, the optimisation problem is formulated using an objective function $F(\mathbf{x},\mathbf{u})$ which is mathematically written using the *exterior penalty function* (EPF) method. The goal of penalty functions is to convert constrained problems into unconstrained problems by introducing an artificial penalty for violating the constraint. In this very specific problem, the EPF is used to introduce the bus voltages (V_i, $i = 1, \ldots, n_{bus}$) constraints in the objective function and transform the objective function to an augmented objective function set for subsequent execution of an unconstrained optimisation algorithm. The augmented objective function $F(\boldsymbol{x}, \mathbf{u})$ is the linear combination of the main objective function $f(\mathbf{x}) = P_{losses}$ and the penalty function $g(\boldsymbol{x}, \mathbf{u})$:

$$F(\mathbf{x},\mathbf{u}) = f(\mathbf{x}) + g(\mathbf{x},\mathbf{u}) \tag{1}$$

where **x** represents the vector of the control variables, in this case, the reactive power output of the DER (continuous, restricted variable) and the transformers tap settings (discrete restricted variable):

$$\mathbf{x} = \begin{bmatrix} x_1 & x_2 & \ldots & x_n \end{bmatrix}^T \tag{2}$$

where:

$$x_i^{\min} \le x_i \le x_i^{\max} \quad \forall \;\; i = 1, \ldots, n \tag{3}$$

The function $f(\mathbf{x})$ represents the initial objective function which is the total active power loses (P_{losses}) for each time period during the time horizon of a single day.

$$f(\mathbf{x}) = P_{lossess}(t_k) \quad \forall \;\; k = 1, \ldots, n_{periods} \tag{4}$$

The penalty function $g(\mathbf{x},\mathbf{u})$ is specifically defined to consider a penalisation when the bus voltages violate the quality limits ($\mathbf{u}^{\min}$, $\mathbf{u}^{\max}$). The coefficient $\mathbf{u} = [k_p]$ represents a penalty multiplier. The penalty function $g(\boldsymbol{x}, k_p)$ is defined as:

$$g(\mathbf{x},\mathbf{u}) = k_p \left[\sum_{j=1}^{N} h_i(\mathbf{x}) \right]^2 \quad (5)$$

where the auxiliary penalisation function h_i is defined as follow:

$$h_i(\mathbf{x}) = \begin{cases} 0, & \text{if } V_i^{\min} < V_i < V_i^{\min} \\ 1, & \text{otherwise} \end{cases} \quad \forall \ i = 1, \ldots, n_{bus} \quad (6)$$

The number of buses with a voltage outside the allowable range is squared, multiplied by the penalty factor and then added to the objective function. By squaring the number of buses with a voltage outside the admissible range, more weight is assigned to the penalty function thereby increasing the objective function in a greater proportion. Nonetheless, the solution obtained might entail a higher value of system losses.

A small penalty factor (k_p) may produce a solution close to the constraint limits. The value assigned to the penalty factor can be set constant throughout the optimisation process, or it can be set so that it varies with each iteration from an initial maximum to a final minimum thereby unfeasible solutions are more heavily penalised at the beginning of the process. In this work, the penalty factor was set constant with a value of k_p =100.

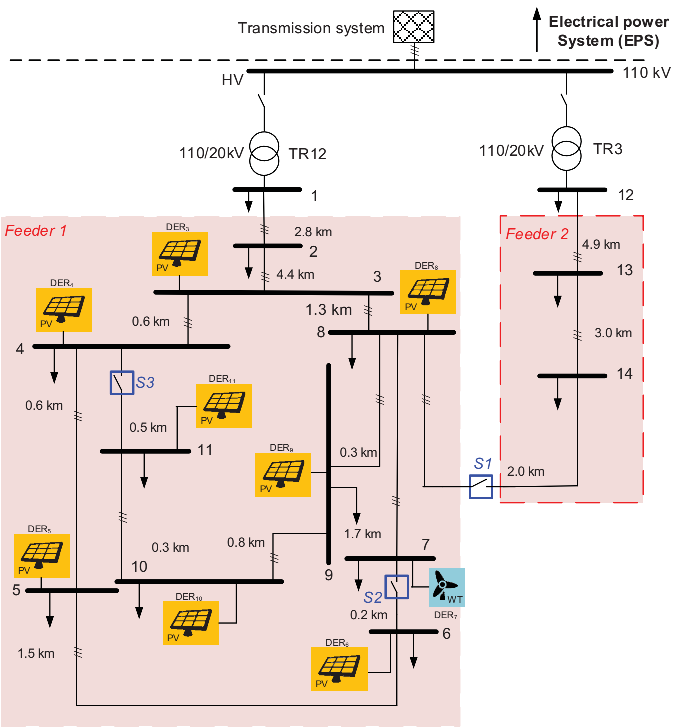

Figure 3. Test System: Single-line diagram depicting the European Distribution of the test system and the integration of DER.

VI. Simulation and Results

The proposed methodology is illustrated in this section. A typical European Distribution of the test system is used for illustrative purposes.

A. *Test System*

The European Distribution of the test system created by the CIGRE Task Force C6.04, and presented in the report titled "*Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources*" [20] has been slightly modified and used for illustrative purposes. The European MV distribution network benchmark does not explicitly include unbalances; as a consequence, the network is assumed to be symmetrical and balanced. The test system consists of two typical European MV distribution 20 kV, 50 Hz, three-phase feeders, named *Feeder 1* and *2* and highlighted in Figure 3. The two feeders include switching devices allowing the feeders to be operated in radial or meshed topology. In this paper, the "*S2*" and "*S3*" switches are considered to be open. The authors have selected the European MV distribution feeders because can be used for DER integration studies.

B. *Methodology application/implementation*

Following the methodology presented in Section V. The objective function considers the total power losses as well as the voltage profile for all system buses (1)-(6). The control variables vector **x** is defined in (2) and its limit expressed in (4). The control variable vector consists of the reactive power injection of the DER, for the case of Figure 3, it consists of the reactive power produced by a wind turbine ($\mathbf{Q_{GWT}}$), the reactive power output of the PV units ($\mathbf{Q_{GPV}}$) and the tap position of the OLTC changers of the power transformers **u**.

$$\mathbf{x} = [\mathbf{Q_{GWT}} \quad \mathbf{Q_{GPV}} \quad \boldsymbol{\lambda}]^T \quad (7)$$

where:

$$\mathbf{Q_{GWT}} = [Q_{GWT}]^T$$

$$\mathbf{Q_{GPV}} = [(Q_{GPV3}\ Q_{GPV4}\ Q_{GPV5}\ Q_{GPV6}\ Q_{GPV8}\ Q_{GPV9}\ Q_{GPV10}\ Q_{GPV11})]^T$$

$$\boldsymbol{\lambda} = [Tap_{0-1} \quad Tap_{0-12}]^T$$

The control variables vector is constrained. It is considered that each transformer has ±10 load changing taps and that each tap corresponds to $|\Delta V| = 0.625\%$ of the transformer rated voltage (tap position cero, $Tap_{0\text{-}1} = 0$, $Tap_{0\text{-}12} = 0$). The reactive power output of DER (Q_{Gi}) is constrained inside the safety operative limits of each unit which are given by the fixed maximum apparent power (Sn_i) and the variable active power injection (P_{Gi}) at each period as defined as:

$$Q_{G_i}(t_k) = \pm\sqrt{\left[S_{n_i}\right]^2 - \left[P_{G_i}(t_k)\right]^2} \quad (8)$$

$$\forall \ k = 1, \ldots, n_{periods}$$

To evaluate the constraints, DIgSILENT® PowerFactory™ is used to calculate the solution of the AC power flow, the solution of the set of the non-linear equations. Also, transformers taps can only take integer values. Therefore, the equations formulated in (6)-(8) correspond to *mixed-integer nonlinear* programming (MINLP) optimisation problem. By formulating the problem as a MINLP more exact results can be obtained as the full complexity of the network is considered and no rounding is necessary to obtain the optimum transformer tap settings. The MINLP optimisation model formulated above is solved efficiently by the open-source C++ code Bonmin (Basic Open-source Nonlinear Mixed INteger programming) [21].

C. Simulation cases and results

The proposed methodology is applied to the *Test system* (shown in Figure 3) considering three simulation scenarios. *Case 1* is showing the system voltages and the relevant losses under normal operation. *Case 2* is about the integration of DER onto the grid as a first step of lowering the losses followed by *Case 3* in which a MINLP optimisation process is performed with the determination of reactive power and applying relevant transformer tap changers.

1) Results of Case 1: No DER – Base Case

From Figure 4, it is evident that due to the low demand both from residential and commercial/industrial consumers in the early hours of the day (from 00:00 to 06:00) the voltages are higher than 1.0 pu throughout the system.

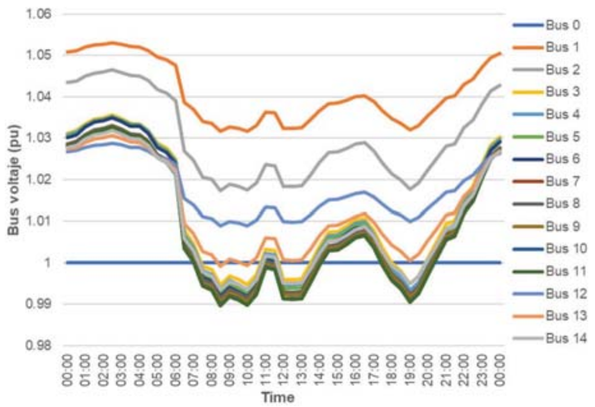

Figure 4. System voltages for the Base Case.

From 00:00 to 06:00, the voltage of bus 1 rise above 1.05 pu. However, after 07:30 overall voltages begin to descend and reach a minimum value of 0.989 pu in Bus 11 at 08:30. Voltage profile improves after 12:00 following a reduction in residential demand, however, after 16:00 they decrease sharply and reach a new minimum of 0.991 pu at 19:00. Figure 5 shows how the active power losses increase sharply at around 07:30 due to increase demand and the maximum value is 130.05 kW at 19:00.

2) Results of Case 2 (Integration of DER)

The total active power losses are reduced by the integration of the DER, and the voltage profiles are improved in the middle part of the day. Notably, the voltage in all buses is within 5 % of the nominal value during the day as opposed to the previous cases without DER. The reduction in system losses can be more readily understood by observing the active power losses shown in Figure 6 after the implementation of DER. For example, the depicted losses at 19:00h are reduced by almost 30 % concerning the base case in Figure 5. The DER introduced, namely, the wind turbine and PV units supply a percentage of the demand locally thereby reducing power lost in transmission.

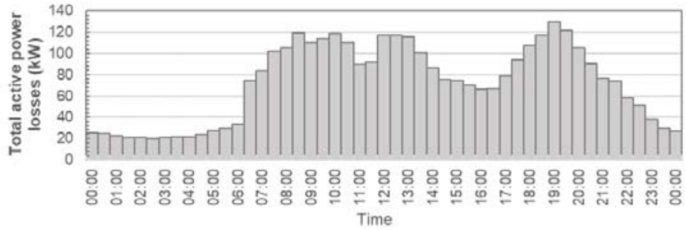

Figure 5. System losses for the *Base Case*.

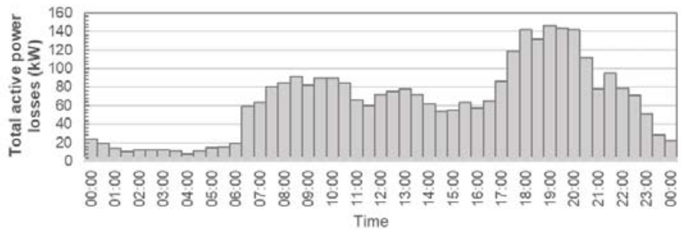

Figure 6. System losses for *Case 2*; Including of DER.

D. Results of Case 3 (Proposed Methodology)

Figure 7 shows the overall system losses for the *Cases 1, 2* and *Case 3*.

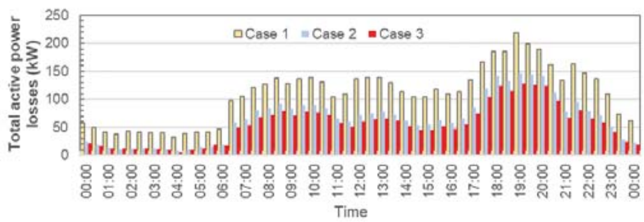

Figure 7. System losses comparison for *Case 1, 2* and *3*.

The inclusion of DER in case 2 effectively reduces the power that needs to be transmitted from the main substation and therefore has the effect of significantly reducing system losses which vary from 7.76 kW at 04:00 to 146.5 kW at 19:00. Finally, in *Case 3*, the reactive power of the DER as well as, the operation of the transformer tap changers is optimised to reduce system losses as well as to keep the voltage profile within 5 % of the nominal values. In this case the system losses at 04:00 are 6.07 kW and the losses at 19:00 are 127.58 kW. The system's peak losses are reduced from 218 kW to 127.58 kW which is an equivalent reduction of almost 60%.

E. Convergence Behaviour

Figure 8 shows the convergence plots for a selection of different load conditions encountered at different times of the day. The algorithm initializes with an exploration stage. Next, after around 10 iterations, it begins to do a series of refinement steps, the purpose of which is to enhance the best solution possible by executing a local check around it, using a variation of a trust region method. After about 40 iterations, the algorithm converges to the optimal solution of the augmented objective function **F(x)**.

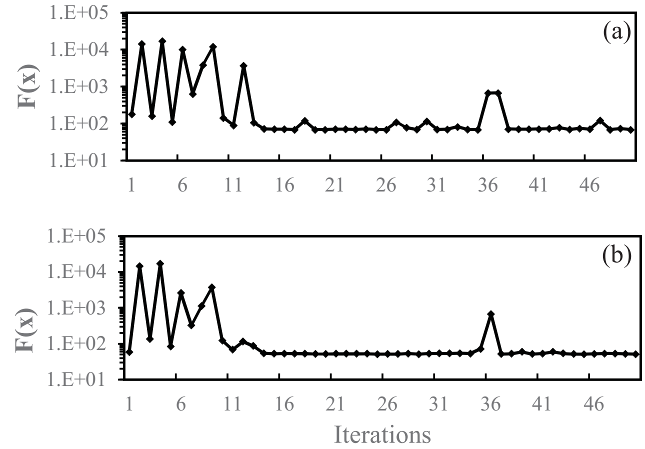

Figure 8. Convergence plots at different load conditions (a) t_k=07:30h. (b) t_k=11:30h.

VII. CONCLUSIONS

The most recent developments power electronics allow creating the grid-friendly or smart–converters and it also allows other tasks that could help the TSO with managing the operational problems: voltage control, low short-circuit currents, etc. This paper is dedicated to introducing the concept of grid-friendly or smart-converters and how they can create a controllable micro-grid able to provide auxiliary services to the transmission system: the so-called "transmission system friendly micro-grid". Also, the paper presented numerical results of the proposed control methodology and its implementation by using Python and power system calculations are performed by DIgSILENT PowerFactory. Numeric results showed and verified the suitability of the proposed transmission system friendly micro-grid.

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