Dynamic Simulation of Fuel Cells and Micro-turbines Integrated with a Multi-Machine Network

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***Abstract*-- The paper discusses aspects of dynamic modelling and simulation of fuel cell and micro-turbine units as a part of a multi-machine electrical network. The focus is on the consideration of a large number of units connected to different low voltage nodes. In the study, the total power generated in decentralized units reaches up to 30% of the 110-kV-network demands. Therefore, it is expected that decentralized sources impact the dynamic behaviour of the high voltage network and vice versa. Hence, the investigated power system comprises also the high voltage grid and the corresponding conventional power plants supplying into this network. To evaluate the performance of the network, various disturbances are applied and the results are discussed.**

***Index Terms*- Dynamic modelling, Fuel cells, Gas turbines, Power system analysis, Stability problem**

I. INTRODUCTION

THE use of the Distributed Energy Resources –DER- represents an important support to the main centralized electrical power plants. The extension of this type of power generation with a large variety of types and capacities became a real fact [1]. It is expected in the near future to utilize more energy from small distributed units [2].

With the increasing rate of DER in the electricity production and their integration into the existing network several problems arise. One of the issues concerns the dynamic interaction of DER with the overlaying network. Until now, such interactions were neglected or solved in such a way that DER, in emergency situations, were disconnected from the network. However, disconnections may lead to more aggravation and thus it is not acceptable in general. Furthermore, controllers located on the network side and DER controller may interact with each other and thus cause unacceptable dynamic behaviour. The problems will assume a new dimension in the near future, when the contributions of DER further increases according to the political and social expectations and technological progress.

Micro-turbine and the fuel cell units are two types of DER, whose performance within a network still needs more investigation. The micro-turbines are known for a long time now as reliable main or back-up sources in a wide field of applications [3]-[6]. Fuel cells are also promising units, which have many advantages. High efficiency, low emission and the possibility of cogeneration are some of them [7].

The dynamic modelling and simulation of the micro-turbine as well as the construction and operation of the fuel cell have been discussed in detail in many literatures [1]-[12]. This mostly included the stand-alone mode or the case where a limited number of units is connected to a small network. The dynamic operation of several units within a multi-machine network, however, is a different task, which remains to be studied.

This paper presents a dynamic-simulation study for the case where many fuel cells and micro-turbines operate within a multi-machine network. The selected DER units are candidate to be used in large scale in the power system especially when the technical solutions for hybrid units consisting of fuel cell and micro-turbine are well developed [12]. Because of the expected interaction with the conventional power plants the high voltage network is modelled in detail. Furthermore, the connection of DER requires modelling of the network down to the low voltage level. Therefore, one 110-kV-network and the underlying voltage levels are modelled too with representative equivalents. The DER units are assumed to cover up to 30% of the total demand at the end-user terminals. This situation differs from the case where a limited number is used, which will have a small effect on the network. The dynamic models for both fuel cells and micro-turbine units, which are accomplished using the simulation tool "*Power System Dynamics* (PSD)" [13], are introduced in this paper. The topology of the multi-machine network is also described and the simulation process is presented. Finally, the performance of the plants will be evaluated on the basis of some simulation results.

II. MODELLING THE PROPOSED SYSTEM

The test system consists of several fuel cells and micro-turbines with various capacities as a part of a multi-machine network. The ratings of these units vary from 150-400 kW for the micro-turbines and from 250 to 500 kW for the fuel cells. Typical configurations and parameters are used to model and simulate the network, which is called "PST16" network denoting the 16 generating units. [14]

A. Network description

Fig. 1 illustrates the layout of the PST16 network.

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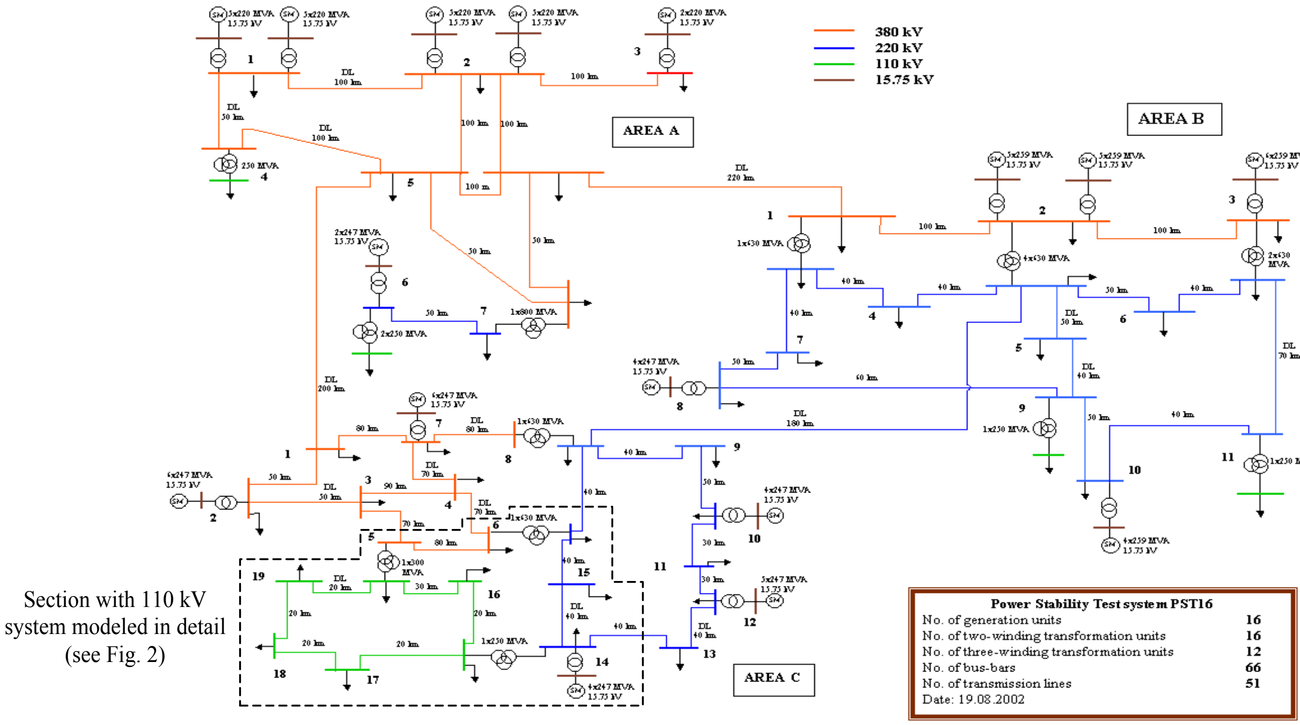


Fig. 1. Single line diagram of the PST16 network

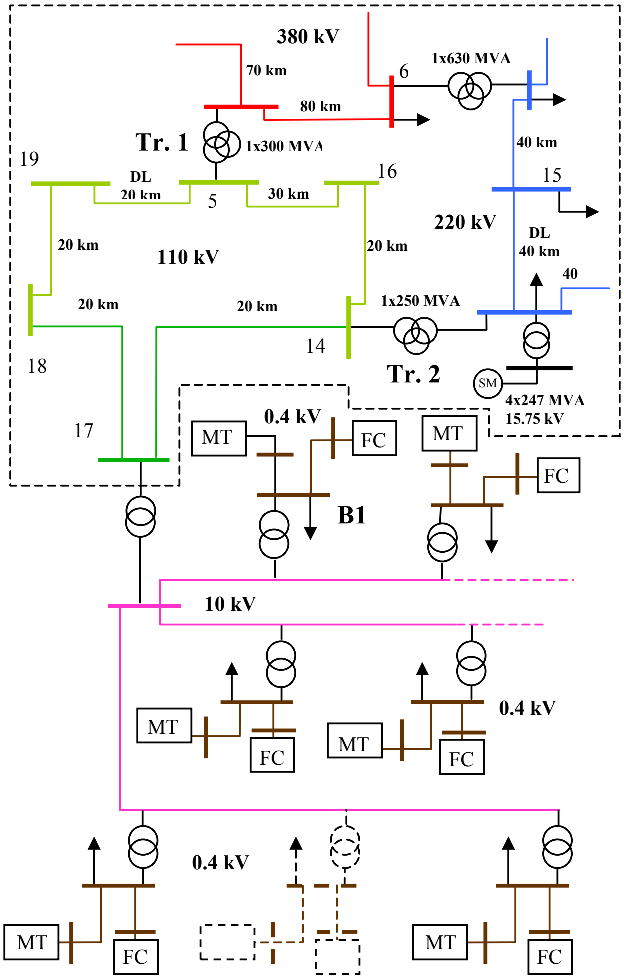
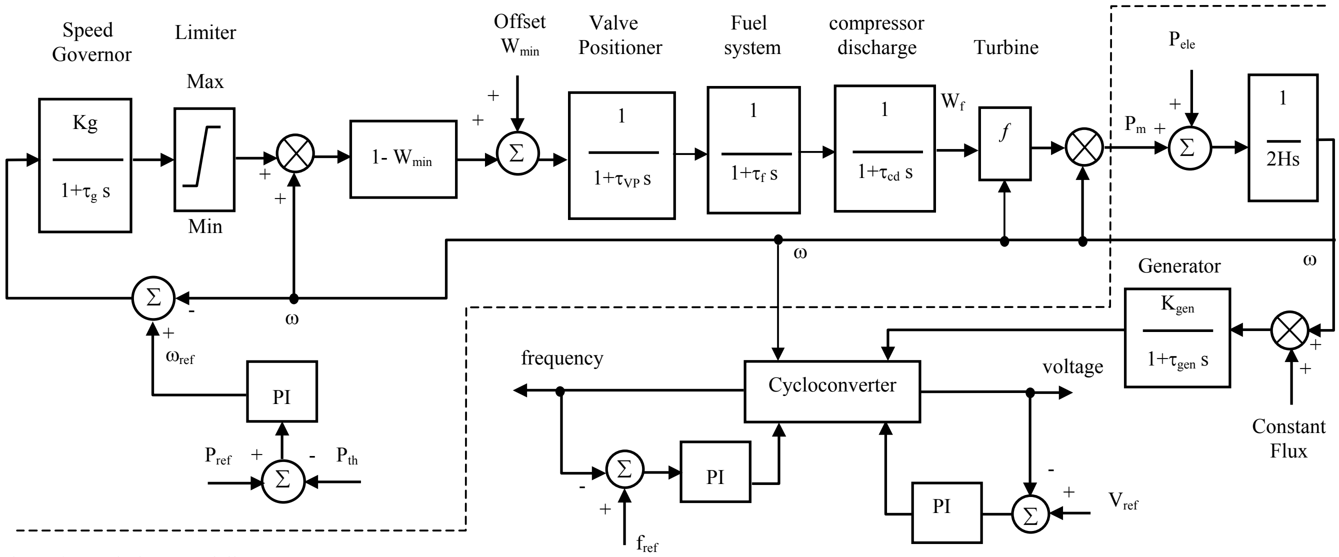


Fig. 2. Network section with details to modelling of medium and low voltage levels and DER network connections

Synchronous generators, connected via transformers to the high voltage nodes are represented by fifth-order models. Among the considered types are thermal, hydro, and nuclear units. IEEE standard regulators are used for modelling the speed governors and the excitation systems. The nominal voltages in the network are 380, 220, 110, 10 and 0.4 kV. For the investigations, one 110-kV-network with the underlying 10- and 0,4-kV-parts are modelled in detail (see Fig. 2). As decentralized energy resources, the fuel cell and the micro-turbine units are located within the electric distribution system at or near the end user at 0.4 kV. Six 110-kV-nodes are chosen in area "C" to accomplish the extension of the network to a low voltage system. Two steps of transformation are required to reach the 0.4-kV-level. The first step is from 110 to 10 kV and the second is from 10 to 0.4 kV. A micro-turbine and a fuel-cell unit are located near each of the 56 nodes in the 0.4-kV-system. The DER units are connected to the load nodes with 100-300 m cables. With this configuration, the loads in the low-voltage area are supplied through two sources: 10/0.4 kV transformers as well as DER units. Note that the power transfer to and from the 110-kV-area is carried out via the 300-MVA-transformer "Tr. 1" and the 250-MVA-transformer "Tr. 2" as shown in Fig.2. For comparison reason, the network is modelled and dynamic behaviour is investigated also without DER units under the same disturbances. In this case the loads, which were always kept constant, were supplied exclusively from the medium voltage side. Furthermore, the voltages at the low voltage nodes are lower because of the higher voltage drops on the lines and transformers.



The main symbols are as follows:
H: inertia constant
K_g, K_{gen}: gains of speed governor and generator respectively
τ_g, τ_{vp}, τ_f, τ_{cd}, τ_{gen}: lag-time constants of speed governor, valve positioner, fuel system, compressor discharge and generator respectively
P_{ele}, P_m, P_{th}: input-electrical, mechanical, and thermal power respectively
V_{ref}, f_{ref}, ω_{ref}, P_{ref}: reference voltage, frequency, angular speed, and thermal power respectively.

Fig. 3. Model of the micro-turbine generating unit

B. Modelling of micro-turbines

Fig. 3 shows the block diagram of the micro-turbine dynamic model [4],[6]. Micro-turbines are small high-speed gas turbines. The three main parts are compressor, combustor, and the turbine. The compressor is used to pressurize the air before entering the combustor. Injected fuel is mixed with the compressed air in the combustor and the mixture is ignited. The mechanical energy is produced when the hot combustion gases flow and expand through the turbine. The turbine drives a permanent magnet synchronous generator (PMSG) connected to its shaft without gearbox. A part of the power produced in the turbine is utilized for driving the air compressor while the rest is converted to electricity in the PMSG.

As the frequency of the generated power from the micro-turbine is very high, a cycloconverter is required to reduce the frequency. However, the cycloconverter is used not only to get normal frequency but also to regulate the unit voltage. For this purpose two PI controllers are implemented. The utilization of turbine exhaust gas is also considered in this study. However, in the cogeneration applications the electrical output is regulated to meet the thermal load demands and not the electricity. This fact is important in understanding the simulation results in Section III. The PMSG is represented in this study by a simple first order model.

The part of the model over the dotted line in Fig. 3 describes the dynamics of the micro-turbine including its three main parts. The blocks under the dotted line represents the machine inertia, the generator model, and the cycloconverter with its controllers. The offset (W_{min}) in the figure represents the fuel demand at no-load condition. The following function is used to simulate the performance of the turbine:

$$f = 1.3(W_f - W_{min}) + 0.5\,(1 - \omega) \qquad (1)$$

The used parameters of the micro-turbine model are given in [4]-[6].

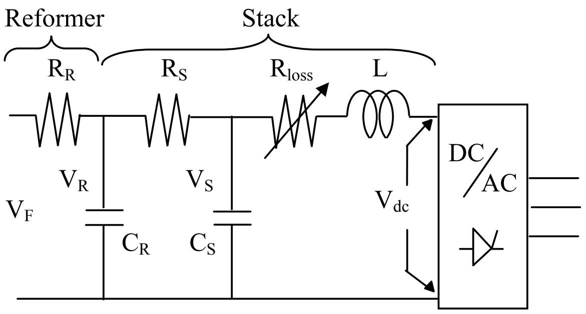
C. Modelling of fuel cells

The fuel cell consists of three main parts: reformer, stack, and power conditioner. The reformer produces a hydrogen-rich gas, which is processed in the stack with air to produce water and heat. As a result of this electro-chemical process, a DC power is produced. The generated DC voltage is converted to AC voltage through the power conditioner. The processes are accomplished at high efficiency, as the fuel cell has no moving parts.

The mathematical modelling of the fuel cell is a complicated process and still need more investigation [8]. The individual components of the system interact with each other in a complex form, where the electrical, chemical, and thermo-dynamic processes are strongly non-linear in nature. Moreover, the parameters of such complex models are difficult to estimate. However, for the stability studies, a third order non-linear equivalent circuit dynamic model is suitable to approximate the fuel cell characteristic behaviour as seen from the network side.

The delay actions in both the reformer and the stack are represented as first-order time delay elements. A non-linear resistance is used to represent all kinds of voltage drop in the stack. This resistance is obtained from the voltage-current characteristics of the fuel cell at steady state. It can also be calculated using the Nernest and Butler-Volmer equations [9],[11]. A non-linear function is developed using the curve fitting technique to drive the resistance as a function of the supplied current. Also an inductor is inserted taking into account the time constant associated with the current. A DC-AC pulse-width modulation (PWM) inverter is used to convert the DC power from the stack to AC power. During the conversion to AC power through the inverter, both the frequency and the voltage from the fuel cell are regulated.

Fig. 4 illustrates the equivalent circuit of the fuel cell used in this simulation study. The time constants vary in the range of 0.8-1.7 s for the reformer and 0.08-0.18 s for the stack depending on the ratings of the unit. Typical V-I-characteristics [9]-[11] are used to develop the loss-resistances as functions of the supplied currents for different types of fuel cells. This includes the proton exchange membrane (PEMFC) for the 250 and 350 kW ratings, the alkaline fuel cell for the 400 kW rating and the solid oxide (SOFC) for the 450 and 500 kW ratings.



The main symbols are as follows:

V_F : input fuel rate
V_R : output from the reformer (input to the stack)
V_{dc} : output DC voltage from the stack
R_{loss} : nonlinear-loss resistance
Time constant of the reformer $\tau_R = R_R C_R$
Time constant of the stack $\tau_S = R_S C_S$

Fig.4. Dynamic equivalent circuit model of the fuel cell

The heat produced from the stack of the fuel cell is high enough to be used in cogeneration applications. The cogeneration will increase the unit efficiency due to the utilization of heat. It is assumed that meeting thermal demand has priority in the full cell control. Furthermore, the ratio of produced electricity and thermal power is always constant. Hence, the increase of the input fuel to the unit will increase the generated electric and thermal power to the same degree. The regulation of the thermal power to meet the thermal load variation is accomplished using a PI controller, which regulates the input fuel rate and hence the thermal power.

The task of the controllers of fuel cell and micro-turbine units is to regulate the performance of the unit itself regardless of the performance of the other units and network requirements. This is the current praxis. However, some sophisticated control strategies are under investigation in accordance with the principle of "virtual power plants"

III. Simulation Results and discussion

To evaluate the performance of the system, different disturbances have been applied and simulated. Fig. 5 shows the response of a selected fuel cell unit when switching on a load of 500+j100 kVA at a 0.4-kV-bus 100m away from the unit in the low voltage system. The reaction of the other units vary depending on their locations with respect to the switching point.

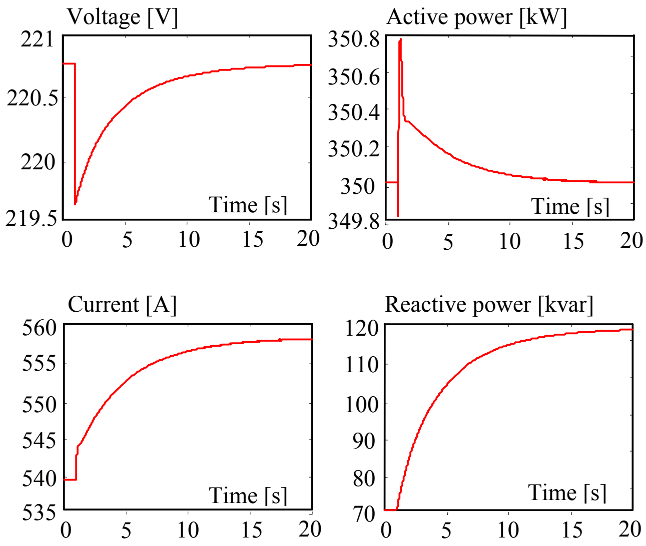


Fig. 5. Response of a selected fuel cell to load switching

The voltage controller succeeded to restore the original value within 20 seconds. As the thermal load demand is assumed to be constant, the set point of the active power controller is maintained also constant. As a result, the active electrical power from the unit is returned back to its initial value in the steady state. The change in the active power demand, however, is covered from the network itself. The reactive power has increased to compensate the voltage collapse occurring as a result of the disturbance. Thus, the terminal voltage moves back to its initial value.

Figures. 6 and 7 illustrate the responses of a micro-turbine and a fuel cell respectively to a 80 ms short circuit in the 380-kV-area. The fault occurred in area "B" at node "1". Generally, the oscillations of the active power of both the fuel cell and micro-turbine are not as strong as those of the reactive power. More damping is achieved due to the direct action of the controllers operating to regulate the active power. On the other hand, the compensation of the voltage variations causes stronger oscillations in the reactive power.

The mechanical nature and the energy stored in the machine mass of the micro-turbines enable large-instantaneous power variations as shown in Fig. 6. The fuel cell, as a static converter, cannot provide such large instantaneous variations in the power and current. With the large increase in the current, the voltage drops sharply and accordingly the internal resistance of the cell increases. The increase of the resistance, which is represented as R_{loss} in Fig. 4, prevents the large increase of the current supplied from the unit. This protects the unit against sudden changes and explains the small variations of the power from the fuel cell compared with the micro-turbine.

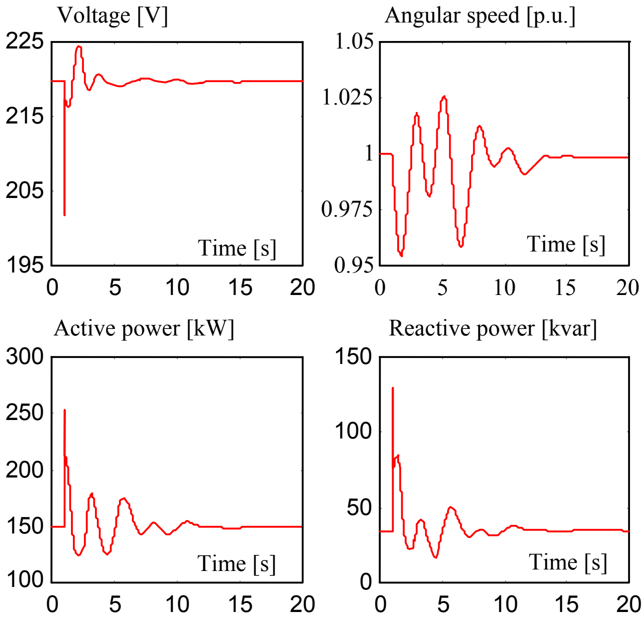


Fig. 6. Reaction of a selected Micro-turbine to a short circuit in the 380-kV-area

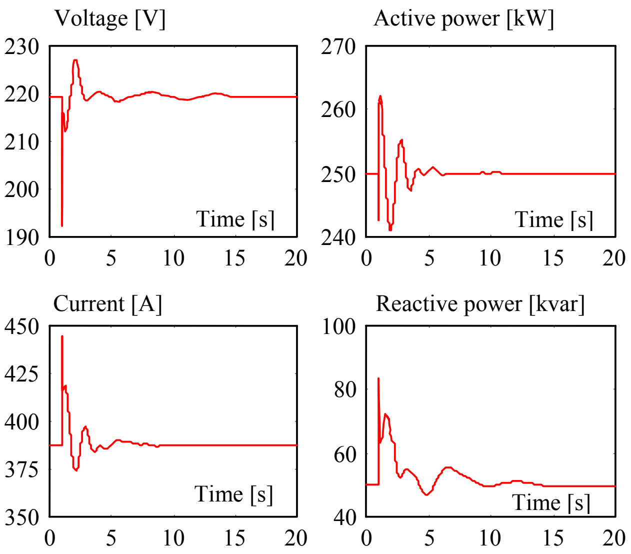


Fig. 7. Reaction of a selected Fuel Cell to a short circuit in the 380-kV-area

Figures 8 through 10 show the behaviour of the network with the abovementioned short circuit. Fig. 8 shows the active power transferred to the 110-kV-area from the other parts in the network. This power transfer occurs through the transformers 380/110 kV “Tr. 1” and 220/110 kV “Tr. 2” shown in Fig. 2.

From Fig. 8 raises the question regarding the strong oscillations in the power transfer to the 110-kV-network. Despite the fact that 30% of the total power demands is produced in the DER units it is obvious that the observed phenomenon can not be explained by the reaction of the DER. However, considering that changes of the active power through transformer 1 are in opposition to those through the transformer 2, it will be clear that the swings are caused by the high voltage system. Parts of the network surrounding the 110-kV-area oscillate against each other through the 110-kV-network. In this relation it is not significant that the voltage levels differ in the connection points (220 and 380 kV) due to the strong connections of this parts

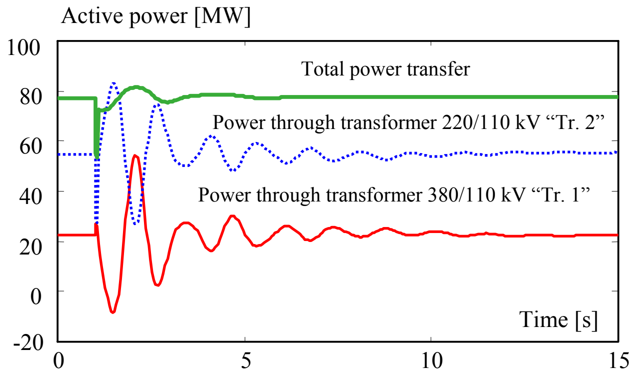


Fig. 8 Active power transferred from the HV area to the 110-kV-network

The effect of the oscillations does not extend to the low voltage area and hence they are not noticeable in the dynamics of the DER units (see Fig. 6 and 7). To compensate the inter-area oscillations appearing in the figure, it is required to regulate the performance of the network as a whole. It is not possible to achieve this objective from the 110-kV-area alone. The focus in this paper, however, is limited to the low–voltage area and DER units. Nevertheless, research activities in the future have to be focused on control actions applied to the DER units to mitigate characteristic high voltage oscillations.

To highlight the effect of the DER unit on the power transfer, Fig. 9 gives a comparison between the change in the total power transfer to the 110-kV-system with and without DER units.

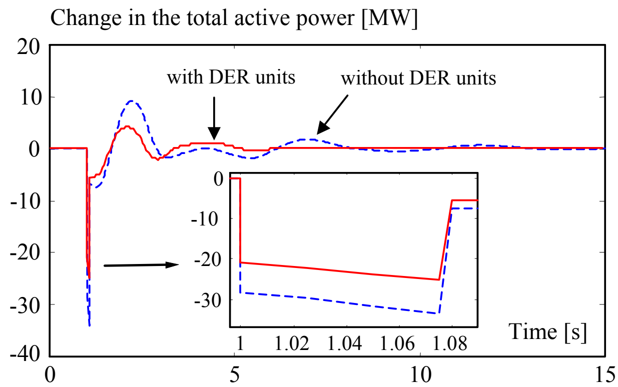


Fig.9 Change in the total active power transfer to the 110-kV-network with and without DER units in sequence of a three-phase short circuit in the 380 kV network

Fig. 10 shows the voltage variations of a 0.4-kV-load-bus "B1" in Fig. 2 as a result of the short circuit with and without the units. The figure shows an increase in the steady state voltage when using the DER units. Without DER units, the load at this node is completely supplied from the network, which causes higher voltage drop over the lines.

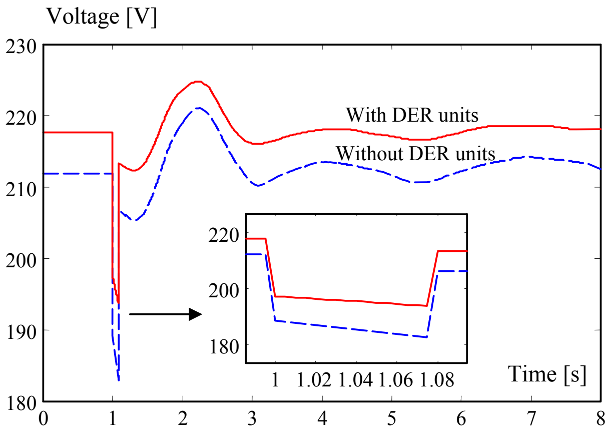


Fig. 10. Voltage variation at a low voltage bus with and without DER units in sequence of a three-phase short circuit in the 380 kV network

IV. Conclusion

In this paper the dynamic behaviour of a hypothetical futuristic power system containing a large number of full cells and micro-turbines has been investigated. The DER units covers up to 30% of the total power demands at the 0.4-kV-level. Because of the expected interaction the system model includes also the high voltage network.

Generally, the results showed that the DER units can absorb, to some extent, large disturbances within the network. However, due to the current concept of controller, DER does not respond to inter-area oscillations or other characteristic high-voltage network phenomena. The results showed also some improvement in the performance of the low-voltage area, which is caused on the one hand by the smaller voltage drop over the low voltage line and on the other by the active voltage sources represented by DER. However, the extended use of the DER units within a network still needs more investigation to manage their performance and to coordinate the operation among the individual units within the whole network.

V. References

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VI. Biographies

Ahmed M. Azmy (1968) was born in Menoufya, Egypt. He received the B.Sc. and M.Sc. degrees in electrical engineering from the Menoufya University, Egypt in 1991 and 1996, respectively. Since 1992, he has worked for the university of Tanta, Egypt in the power engineering and electrical machines department. He started his Ph.D. in the university of Duisburg, Germany at 2001 through a scholarship financed by the Egyptian government. His subject in the Ph.D. thesis is the Modelling and Intelligent management of Interconnected Decentralized Power Generating units.

István Erlich (1953) received his Dipl.-Ing. degree in electrical engineering from the University of Dresden/Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to 1998, he worked with the consulting company EAB in Berlin and the Fraunhofer Institute IITB Dresden respectively. During this time, he also had a teaching assignment at the University of Dresden. Since 1998, he is Professor and head of the Institute of Electrical Power Systems at the University of Duisburg/Germany. His major scientific interest is focused on power system stability and control, modelling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and IEEE.