DYNAMIC SIMULATION OF HYBRID FUEL CELL/MICRO-TURBINE UNITS INTEGRATED INTO LARGE POWER SYSTEMS

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Abstract- The paper presents dynamic models and corresponding simulation results of hybrid fuel cell / micro-turbine units integrated into the low-voltage part of a large network. It is assumed that up to 30% of the total electricity demand in the low-voltage area will be covered by these units. The study aims to highlight the dynamic interaction of several units with each other and with the high-voltage systems of the network. For this purpose, about 56 hybrid units are modelled and connected to different nodes in the low voltage area. The high voltage system is also described in detail. Two technological configurations for hybrid operation are discussed and suitable dynamic models are developed. System performance is evaluated by simulating some disturbances in the high voltage part. The response of separate units, where fuel cell and micro-turbine are operating without any constructional connections, is also illustrated at the same conditions. The objective is to identify the difference in dynamic behaviour of the hybrid sources with respect to the separate units.

I. INTRODUCTION

Distributed generating units are expected to spread rapidly within the power system [1]. A great attention is exerted to increase their efficiencies to achieve economical operation. Micro-turbines produce low cost low emission electricity but at low efficiency which is limited by the combustion process [2-6]. Fuel cells offer the potential for lower emissions and high efficiency but are likely to be too expensive for many applications [7-8]. Higher efficiency can be achieved by coupling a high-temperature fuel cell (>600°C) to a micro-turbine. The advantages of this configuration include: high efficiency, fuel flexibility, superior environmental performance, lower capital cost per unit power and possibility of independent operation of the units [9]. It is expected to deploy the first fuel cell/micro-turbine hybrid unit in the commercial market by fall 2003.

The development of the fuel cell and the micro-turbine has been discussed in many technical literatures [1-8]. The construction of the hybrid unit and some technical aspects are also discussed in some researches [9,10]. The dynamical behaviour of the augmented unit as well as the integration of these units with a multi-machine network are other approaches, which still need to be investigated. The dynamic interdependencies between the fuel cell and the micro-turbine, the system transient performance, and the dynamic control requirements are some points, which have to be highlighted.

In a previous research, the performance of several fuel cells and micro-turbines as decentralized energy sources integrated with a multi-machine network is investigated [11]. This also included the impact of the dynamics of such units on the performance of the network and vice versa. The fuel cell and the micro-turbine showed a satisfactory operation within the network and provided some enhancements to the performance of the distributed system.

In this paper, the research is extended to cover the construction and simulation of a fuel cell/micro-turbine hybrid unit. The structure of the hybrid unit is discussed and a suitable dynamic model using the simulation tool Power System Dynamics “PSD” is developed. Some results are introduced to evaluate the performance under selected disturbances in the high-voltage area. To compare with the conventional system, the response of separate units to one disturbance is also illustrated.

II. UNIT STRUCTURE

A Combined Fuel Cell/Micro-Turbine “CFCMT” unit consists of a high-temperature fuel cell with an internal reformer, an air compressor, a high speed-low capacity gas turbine, and a permanent magnet (PM) synchronous generator. The exhaust air from the fuel cell, which still contains energy, can be used to drive the downstream turbine replacing the classical combustor. Another approach is to utilize the residual energy in the power cycle more efficiently by using the hot exhaust from a turbine as an air supply to the fuel cell. The former configuration is known as the “topping mode” while the latter is called the “bottoming mode”. SOFC can operate effectively in the “topping” mode due to its high temperature which reaches 1000°C, while molten carbonate fuel cell, which operates at 650°C, is more suitable for the “bottoming” mode [10].

a. Topping mode

In the topping mode, the fuel cell replaces the classical combustor of the gas turbine. In this case, the compressor is used to pressurize the air before entering the fuel cell, which enhances the performance of the unit and increases the efficiency. An internal reformer is used to produce a hydrogen rich reformed gas. The gas is electrochemically processed in the stack to produce water, heat, and DC power. A downstream turbine is used to extract more power by expanding the exhaust gas from the fuel cell as a working fluid. The generated power from the turbine is used to drive the electric motor with the compressor and to produce AC power through the PM generator.

The exhaust from the turbine is used to preheat the air before entering the fuel cell using a heat exchanger. A power conditioner is used to convert the fuel cell power from DC to AC. The high frequency power from the generator is reduced using a cycloconverter, which is also used to regulate the terminal voltage. A start up combustor is used to drive the turbine and in some cases it is also used in the running mode to increase the power from the turbine. Fig. 1 illustrates the configuration of the topping-mode showing the main components.

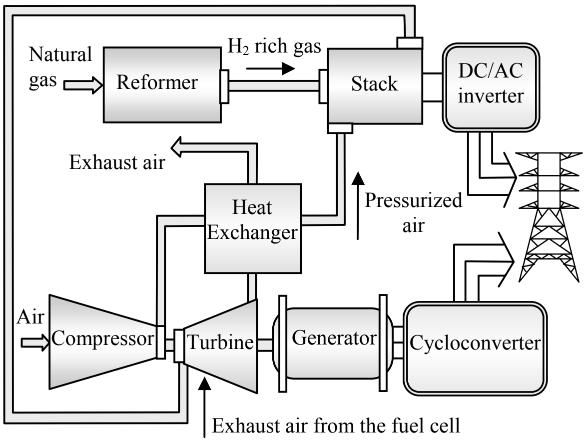


Fig. 1. The augmented unit (Topping mode)

b. Bottoming mode

In the bottoming mode, it is possible to use the exhaust air from the turbine directly as an air supply for the fuel cell. In another configuration an oxidizer can be used as shown in Fig. 2 [10]. The inputs to the oxidizer are the exhausts from the stack and the turbine. The output from the oxidizer is used in the heat exchanger to increase the temperature of the pressurized air before entering the turbine. The turbine power is used to drive the motor of the air compressor through a shaft between them and to produce AC electrical power within a PM synchronous generator. This paper focuses only on the topping mode as it represents a more established technology while the bottoming construction is still under consideration [9].

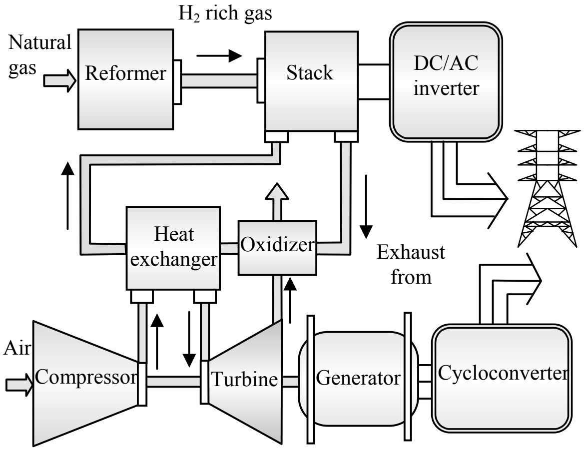


Fig. 2. The augmented unit (Bottoming mode)

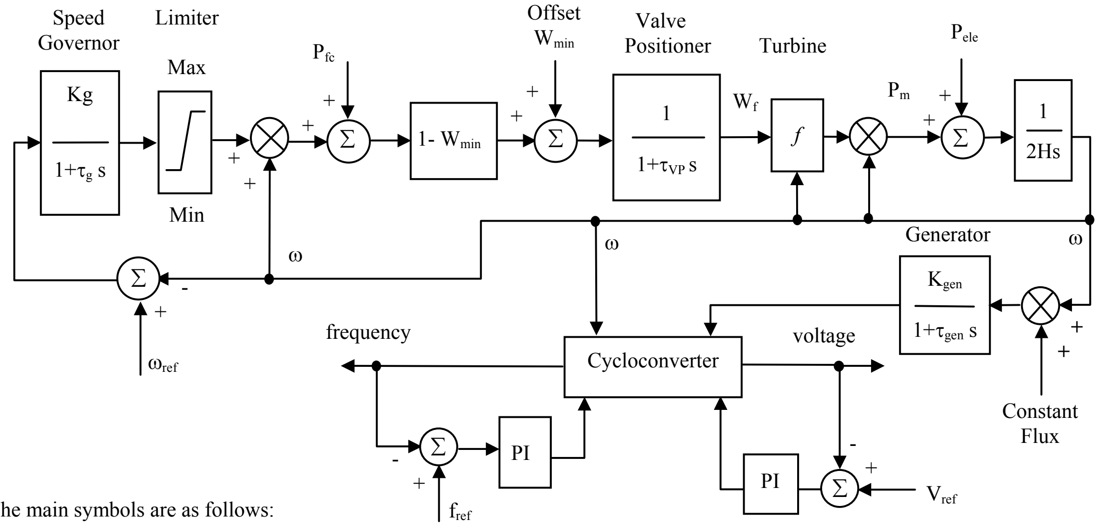
III. DYNAMICAL MODELLING

The fuel cell consists of three main parts: reformer, stack, and power conditioner. The model of the fuel cell, which is introduced in a previous work [11], involves first-order time delay elements to represent the delay actions in both the reformer and the stack. 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 in steady state. It can also be calculated using the Nernest and Butler-Volmer equations [7,8]. A non-linear function is developed to derive 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. The fuel cell is assumed to work independently on the micro-turbine as it has its own fuel source and controllers. The inputs and outputs of the unit are not directly affected by the micro-turbine dynamics.

To model the dynamic interdependency with the abovementioned construction, the turbine mechanical power is assumed to depend on the energy contained in the exhaust air from the fuel cell. This energy is assumed to be proportional to the output electrical power from the fuel cell. The speed governor regulates the angular speed by controlling the amount of exhaust gas utilized by the turbine and rejecting the remainder.

Fig. 3 shows the block diagram of the micro-turbine where some modifications are introduced to the standard model [4-6]. A signal representing the power contained in the fuel-cell exhaust “P_{fc}” is added to the output signal from the speed governor.



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

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

Fig. 3. Model of the micro-turbine generating unit including an input signal representing the power from the fuel cell exhaust

The output from the governor represents the rejected exhaust to control the angular speed. This sum, which represents the net exhaust, is used as an input to the turbine. A similar structure can also be used if an additional combustor is assumed. In this case, the exhaust from the fuel cell contains and provides the basic energy to the turbine while the fuel source, which is regulated by the speed governor, can add more power to that contained in the exhaust air.

IV. NETWORK DESCRIPTION

The investigated system comprises several augmented units in the low voltage area of a multi-machine network. Fig. 4 shows the single line diagram of the network which has 16 generating unit and is called Power Stability Test system “PST16” [12]. Thermal, nuclear and hydro units are considered and represented by fifth-order models. To extend this network to the low voltage level, two transformation steps are used starting from six chosen-110-kV nodes in area “C” as shown in Fig. 5. A total number of 56 hybrid units are used in the distribution system near the end-user terminals. The power from the hybrid units reaches up to 30 % of the total demand in the 110-kV area.

The expected impact of such power on the high voltage part, which is discussed for separate units in a previous paper [11], gives the reason of utilizing up to 380kV system. When connected with a turbine, the fuel cell can produce from 55 to 90% of the electricity of the system while the turbine produces the reminder [10]. The 56 hybrid units are modelled with different capacities varying from 400kW up to 900kW. Depending on capacities of the individual units, the percentage power from the fuel cells vary in the range of 55.6 to 77% of the total hybrid units power. The parameters used in the modelled units vary depending on their capacities.

V. SIMULATION RESULTS AND DISCUSSION

An attempt to regulate the performance of the turbine through the fuel source, which regulates the power of the fuel cell and hence the mechanical power, failed to achieve a satisfactory operation. At the same time where the turbine performance is improved the reaction of the fuel cell seems to be poor and vice versa. It is recommended to use separate controllers with each part of the unit, which is found to give better results, and therefore it is applied in this research.

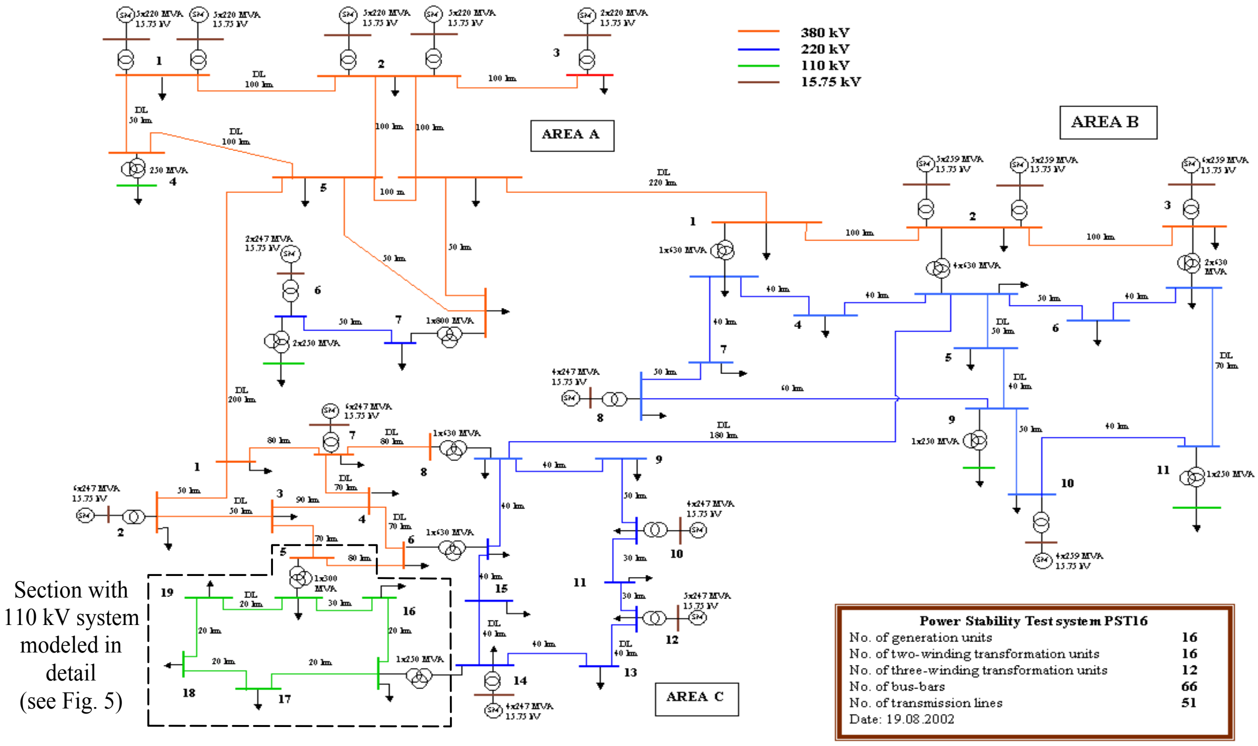


Fig. 4. Single line diagram of the PST16 network

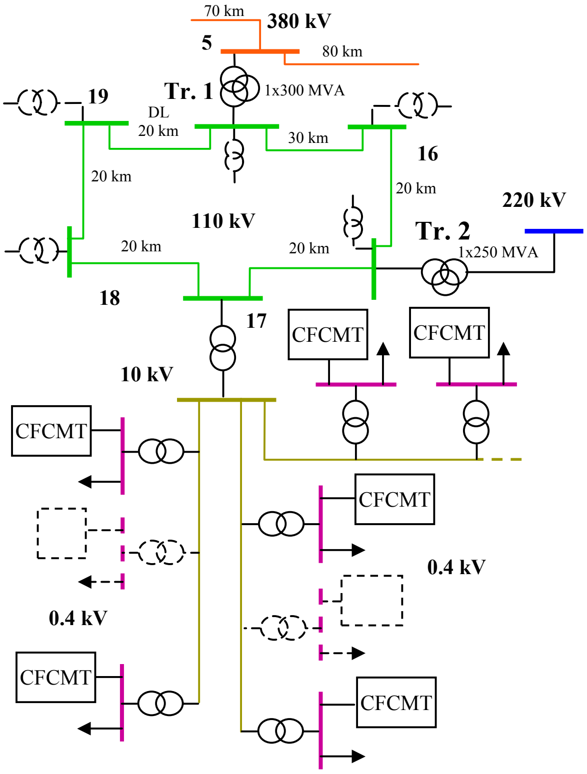


Fig. 5. A part of the PST16 network with some CFCMT units

Fig. 6 illustrates the response of a selected hybrid unit to a 100+j20MVA load switching at a 220-kV bus in area B. The decentralized units and the generators share in covering the additional power. As the switching point is away from the units, they are not strongly affected by the disturbance and therefore a small variation in the power has occurred.

An instantaneous acceleration has occurred for the PM generator after the load switching although the output electrical power has increased. A similar variation in the electrical power of normal unit may cause a deceleration. In the hybrid configuration, both the turbine input mechanical power, which is defined by the fuel cell electrical power, and output electrical power are changed. The fast rise in the fuel cell electrical power, which exceeds that of the turbine, caused an increase of the mechanical power. This results in an acceleration of the PM generator.

The response of another CFCMT to a 80ms-three phase short circuit at a 380-kV bus in area A is shown in Fig. 7. The unit succeeded to restore the initial conditions within 20s after the fault clearance. The oscillations of the reactive power can be explained regarding the controller action to compensate the voltage variations. The decrease in the turbine electrical power and the increase of its mechanical power, due to the increase of fuel cell power, forced the angular speed to instantaneously increase after the fault clearance.

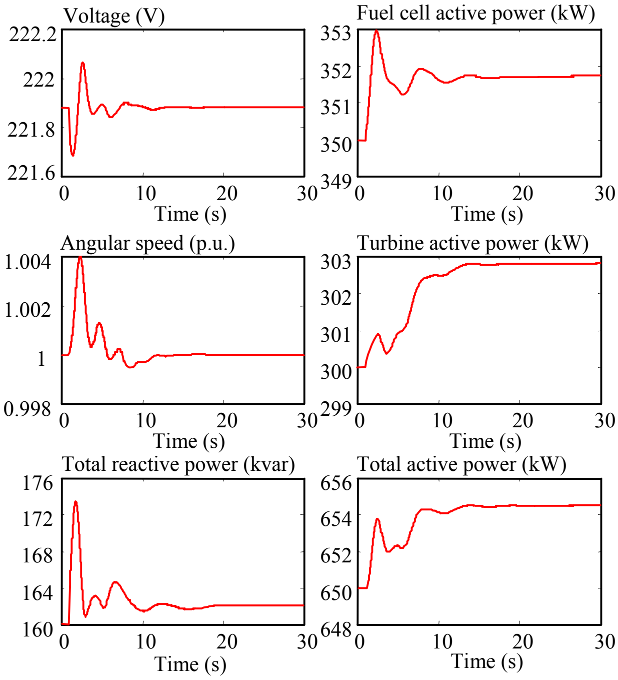


Fig. 6 Response of a selected hybrid unit to a 100 + j20 MVA load switching in the high-voltage area

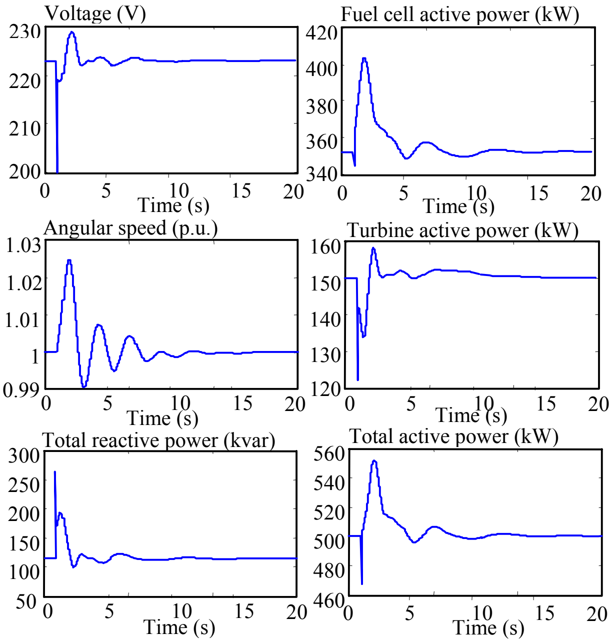


Fig. 7 Response of a hybrid unit to 80 ms short circuit in the high-voltage area

Compared with the behaviour of two parallel individual units (Fig. 8) there is a similarity in the voltage, which is defined by the network rather than the units. As a result, the reactive power varies in the same manner although it has relatively stronger oscillations in the case of hybrid unit. On the other hand, both the active power and the angular speed react differently. This means that the main effect of the hybrid structure is on the active power and the related variables.

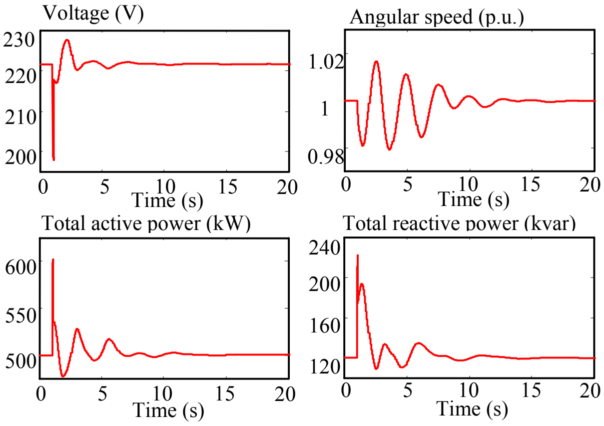


Fig. 8 Response of two individual units in parallel to 80 ms short circuit in the high-voltage area

Fig. 9 gives a comparison between the change in the total power transfer to the 110-kV-system without units, with separate units operating in parallel and with hybrid units. This power transfer occurs through the transformers: 380/110 kV "Tr. 1" and 220/110 kV "Tr. 2" shown in Fig. 5.

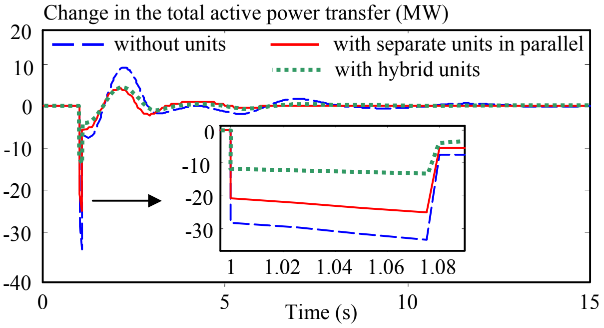


Fig. 9. Change in the total power transferred to the 110-kV-area in 3 different cases due to a 3-phase short circuit in the 380 kV network

The existence of decentralized units near the end user in both cases caused, to some extent, more damping as shown in the figure. The comparison shows also that both parallel operation and hybrid configuration are likely to be similar from the damping point of view. However, a significant reduction in the power variation during the fault occurs with the existence of the hybrid units. This emphasizes the previous result of lower active power variation in the faulty system.

VI. CONCLUSION

The dynamic performance of a hybrid fuel cell/micro-turbine unit using the simulation tool "Power System Dynamics (PSD)" is analysed. Two integration methods to construct the hybrid configuration are discussed. A dynamic model is developed and used to investigate the performance of the augmented unit within a multi-machine network. Some results are introduced to show the response of the proposed units to disturbances in the high-voltage part of the network. A response of separate units operating in parallel to one disturbance is also presented to identify the dynamic interdependency of the unit under consideration. The active power is found to be significantly affected by the new structure due to the impact of the fuel cell dynamics on the turbine power. A similar behaviour from the reactive power is obtained due to its dependency on the terminal voltage, which is defined by the network rather than the individual units. Experimental results and measurements are still required to support the theoretical study in this new field.

VII. REFERENCES

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