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Operating stationary fuel cells on power system and micro-grids

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***Abstract*— The integration of stationary fuel cells for dispersed power generation is a challenge for utilities and service provider in the next few years. Local distribution companies have to assess the impact of distributed generation on power system planning, operation, protection and tariff. Service providers have the opportunity to power micro-grids by fuel cells. Rating of fuel cells and limitations of connectable power are discussed. The impact on protection scheme of power systems and micro-grids are described. Remedial measures are proposed to ensure safety and selectivity.**

***Index Terms*— Fuel cells, dispersed generation, interconnection, protection, isolated operation, micro-grid**

I. Introduction

PROLIFERATION of distributed generation makes new demands on local distribution companies [1]. Liberalization of electrical energy market offers great opportunities for development and marketing of dispersed generation. Fuel cells are developed for a wide range of applications. Stationary fuel cells for dispersed generation are one field of application. This paper considers fuel cells as dispersed generators, but a lot of results are applicable to other distributed energy converters.

Fuel cells connected to power system are suitable for cogeneration of heat and power due to high ratio of electric to thermal power of about one and a part-load capability at a high efficiency [2]. Hence fuel cells are appropriate to supply manufacturing plants and department stores as well as office, public and residential buildings [3].

Stationary fuel cells may be used as an uninterruptible or back-up power supply or to supply a micro-grid. A micro-grid with fuel cells may be an alternative to supply remote and undeveloped areas with electrical energy. Economic efficiency may be achieved more easily for this range of applications.

A dynamic simulation model using EMTDC program was developed in order to investigate the impact of fuel cells on power system and micro-grids [4]. The results of simulations on model networks with dispersed fuel cells will be discussed. The first part of this paper describes impact on power system by dispersed fuel cells. Recommendations are given for simple and efficient integration of fuel cell systems into the power system. The second part deals with fuel cells supplying a micro-grid. Special considerations are necessary to ensure safety, selectivity and a high power quality at micro-grids.

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II. Interconnection of Fuel Cells with Power System

A. Limits of power injection

Rated power is determined dependent on operation modes, e.g. current-controlled operation or heat-controlled operation. Power injection of dispersed fuel cells is limited by requirements of power system, i.e.:

- voltage variation at point of common coupling (PCC) [5], [6],
- permissible voltage range of network [7] and
- current carrying capacity of devices.

Present guidelines permit a voltage variation at the weakest PCC of 2% for distributed generators. That requires extensive load flow calculations at every low voltage network and is not feasible with increasing number of small dispersed generators [8]. Stationary voltage variation can be calculated by means of short-circuit power and angle at PCC as well as rated power and power factor angle of fuel cell (Equation (1)).

$$\Delta \underline{u}_{\mathrm{PCC}}\ [\mathrm{p.u.}] = \frac{S_{\mathrm{FC}}}{S_{\mathrm{sc,PCC}}} \cdot e^{j\cdot(\psi_{\mathrm{sc,PCC}}-\varphi_{\mathrm{FC}})} \tag{1}$$

with:
$S_{\mathrm{sc,PCC}}$ - short-circuit power at PCC
$\psi_{\mathrm{sc,PCC}}$ - short-circuit angle at PCC
S_{FC} - complex power of fuel cell
φ_{FC} - power-factor angle of fuel cell

Absolute value of resulting voltage variation at PCC is calculated by vector addition and is given at equation (2). Figure 1 displays resulting voltage variation at PCC depending on short-circuit power at PCC and power injection of dispersed fuel cell. With a short-circuit power of 2.0 MVA and a short-circuit angle of 30° at PCC an active power feed-in of 40 kW leads to a voltage rise of 1.7%. At the same PCC a power injection of 40 kVA with an inductive power factor of 0.95 (φ_{FC} = 18.2)° results in a voltage rise of 1.96%. If short-circuit angle is unknown or power factor of fuel cell varies, the graph with a difference of angles of 0° is to choose to consider the worst case scenario.

$$|\Delta \underline{u}_{\mathrm{PCC}}|\ [\mathrm{p.u.}] = \sqrt{1+2\cdot\frac{S_{\mathrm{FC}}}{S_{\mathrm{sc,PCC}}}\cdot\cos(\psi_{\mathrm{sc,PCC}}-\varphi_{\mathrm{FC}})+\frac{\mathrm{S}^2_{\mathrm{FC}}}{\mathrm{S}^2_{\mathrm{sc,PCC}}}}-1 \tag{2}$$

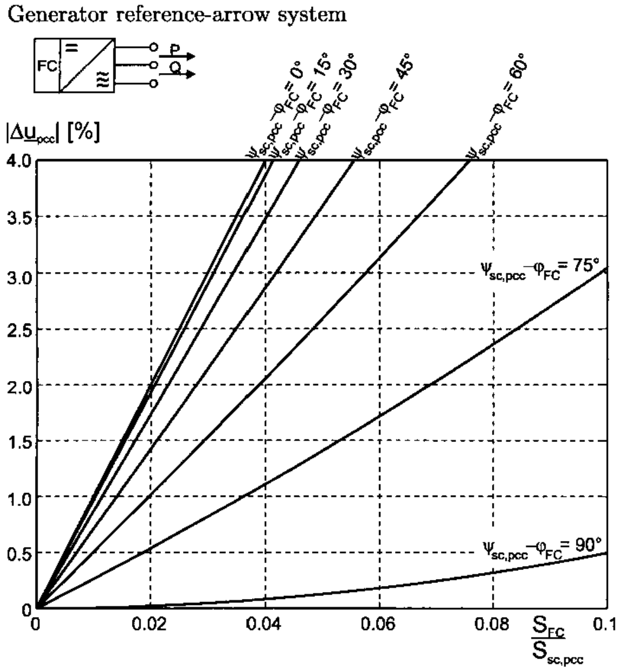

Fig. 1. Absolute values of resulting voltage variation at PCC

The maximum power injection can be calculated depending on permissible voltage variation $\Delta U_{\mathrm{PCC,max}}$ by means of equation (3).

$$S_{\mathrm{FC,max}} = S_{\mathrm{sc,PCC}} \times \left[\sqrt{-\sin^2(\psi_{\mathrm{sc,PCC}} - \varphi_{\mathrm{FC}}) + (\Delta U_{\mathrm{PCC,max}} + 1)^2} - \cos(\psi_{\mathrm{sc,PCC}} - \varphi_{\mathrm{FC}}) \right] \quad (3)$$

Single-phase power injection leads to a voltage variation at all three phases of PCC. Voltage variation at PCC with power injection into phase L1 is given at equations (4) to (6). Equal impedances at positive-sequence and negative-sequence are assumed at these equations.

$$\Delta \underline{U}_{\mathrm{L1,PCC}} = \left(2 + \frac{\underline{Z}_0}{\underline{Z}_1}\right) \times \frac{S_{\mathrm{L1,FC}}}{S_{\mathrm{sc,PCC}}} \times e^{j\cdot(\psi_{\mathrm{sc,PCC}} - \varphi_{\mathrm{L1,FC}})} \quad (4)$$

$$\Delta \underline{U}_{\mathrm{L2,PCC}} = \left(\frac{\underline{Z}_0}{\underline{Z}_1} - 1\right) \times \frac{S_{\mathrm{L1,FC}}}{S_{\mathrm{sc,PCC}}} \times e^{j\cdot(\psi_{\mathrm{sc,PCC}} - \varphi_{\mathrm{L1,FC}})} \quad (5)$$

$$\Delta \underline{U}_{\mathrm{L3,PCC}} = \left(\frac{\underline{Z}_0}{\underline{Z}_1} - 1\right) \times \frac{S_{\mathrm{L1,FC}}}{S_{\mathrm{sc,PCC}}} \times e^{j\cdot(\psi_{\mathrm{sc,PCC}} - \varphi_{\mathrm{L1,FC}})} \quad (6)$$

Voltage variation depends on ratio of zero-sequence impedance ($\underline{Z}_0$) to positive-sequence impedance ($\underline{Z}_1$). If zero-sequence impedance equals positive-sequence impedance, influence of phases L2 and L3 vanish. Voltage variation at phase L1 equals three-phase power injection. Since single-phase power injection is referred to three-phase short circuit power at PCC, a factor of three results from equation (4). Equal impedances at all symmetrical components occur at distribution transformer. With increasing distance from distribution transformer, zero-sequence impedance increases and hence voltage variation increases. At a ratio of zero-sequence impedance to positive-sequence impedance of four, voltage variation of single-phase power injection is twice as three-phase power injection.

Single-phase power injection has to be symmetrically spread over all three phases in order to equalize current at neutral conductor and reduce voltage variation. Present guidelines limit single-phase power injection to 4.6 kVA.

B. Short-circuit performance of fuel cells with three-phase connection to power system

The examined low voltage network is shown at figure 2. The low voltage network is simulated as a radial network. Star-point of distribution transformer at secondary substation is direct grounded (TN-C-system). Three-phase and single-phase inverters of dispersed fuel cells are connected to network.

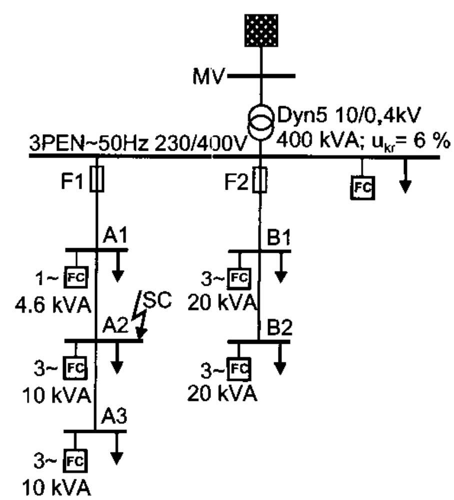

Fig. 2. Single line diagram of examined low voltage network corresponding to figures 3, 4 and 5

Short-circuit performance of fuel cells is determined by control of inverter. Since inverter is current controlled at inner control loop, fuel cell contributes maximally their rated current to network during short-circuit. Figure 3 shows results of a simulation of a fuel cell with three-phase inverter. A remote three-phase short-circuit occurs at time T_{SC} on node A2 and voltage drops to 70% of nominal network voltage. The fuel cell with a rating of 20 kVA feeds their rated current of 29 A to network. Current injection remains the same during short-circuit. Power injection decreases to 70% of rated power due to reduced voltage at PCC. Fuel cell is disconnected from power system by undervoltage protection relay after 50 ms. The fault is cleared after 100 ms by overcurrent protection of the faulted feeder at secondary substation and voltage restores.

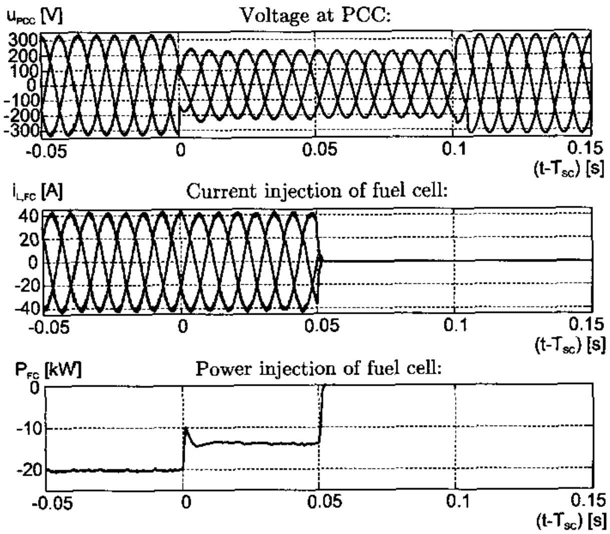

Fig. 3. Short-circuit performance of fuel cell with three-phase power injection at node B1 (figure 2)

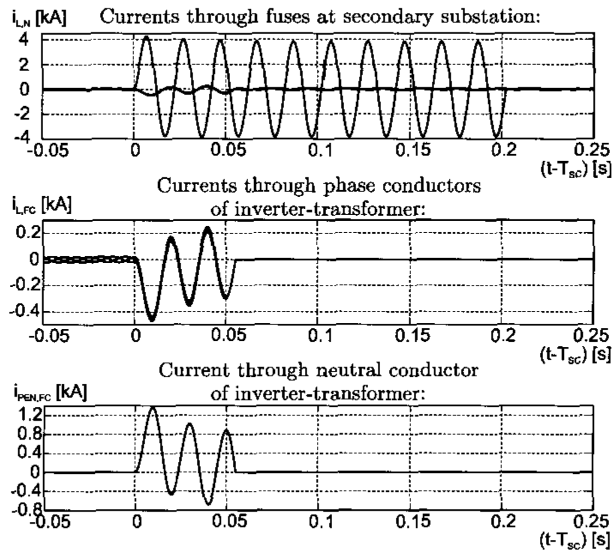

Fig. 4. Short-circuit performance of fuel cell with inverter-transformer at node A3 (figure 2)

Neutral point connection of inverter transformer of dispersed fuel cells may influence unsymmetrical faults to earth, like single-phase or two-phases-to-earth faults. A direct grounded star-point of inverter-transformer reduces zero-sequence impedance. Hence high zero-sequence current flows through the inverter transformer. Figure 4 shows currents through phase conductors and neutral conductor of a three-phase fuel cell with direct grounded inverter-transformer during single-phase-to-earth short-circuit. A single-phase-to-earth short-circuit at phase L1 on node A2 occurs at time T_{SC} and current at faulted feeder increases to 2.8 kA at secondary substation. This current splits at zero-sequence and part of zero-sequence current flows via neutral conductor to star-point of inverter-transformer. High zero-sequence current at phase conductors of fuel cell inverter-transformer trip overcurrent protection at network connection in this case after 50 ms. Single-phase fault is cleared after 200 ms by overcurrent feeder protection at secondary substation.

Fuel cells with isolated inverter-transformer do not influence zero-sequence and hence no zero-sequence current flows through inverter-transformer. If inverter of fuel cell is connected transformeless to power system, control of inverter has to measure and limit current injection into neutral conductor.

C. Short-circuit performance of fuel cells with single-phase connection to power system

Short-circuit performance of fuel cell with single-phase inverter is described at figure 5. A single-phase-to-earth short-circuit at phase L1 on node A2 occurs at time T_{SC} and phase-to-earth voltage of phase L1 drops to 43% of nominal value. Current injection of a fuel cell with rated power of 4.6 kVA at phase L1 keeps constant during single-phase short-circuit until undervoltage protection relay disconnects fuel cell here after 50 ms. Power injection of fuel cell with double frequency, due to single-phase connection, is shown at figure 5. Power oscillation can be decoupled from fuel cell stack by an electrical energy storage. Power output decreases to 43% of rated power during short-circuit, due to voltage reduction at PCC of phase L1, until disconnection of fuel cell. Overcurrent feeder protection of Phase L1 trips here after 200 ms and the single-phase fault is cleared.

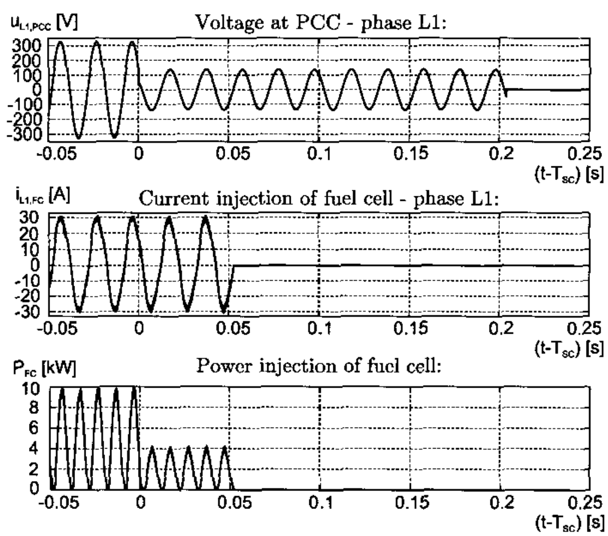

Fig. 5. Short-circuit performance of fuel cell with single-phase power injection at node A1 (figure 2)

D. Impact on protection scheme

Voltage drop during a short-circuit may trip undervoltage protection relay's of fuel cells at faultless feeders, if tripping time of feeder protection is longer than tripping time of undervoltage protection relay. Figure 6 represents the examined medium-voltage model network. Medium voltage network is simulated as an open ringed network. Fuel cells are connected at medium-voltage and subordinated low-voltage networks. Figure 7 shows the simulated RMS-values of node voltages on low-voltage side of distribution transformers during a three-phase short circuit at medium-voltage node A2. Voltages on all subordinated low-voltage networks drop below 0.8 p.u. and hence undervoltage protection relay's of fuel cells trip and disconnect fuel cells from power system (in this case 50 ms).

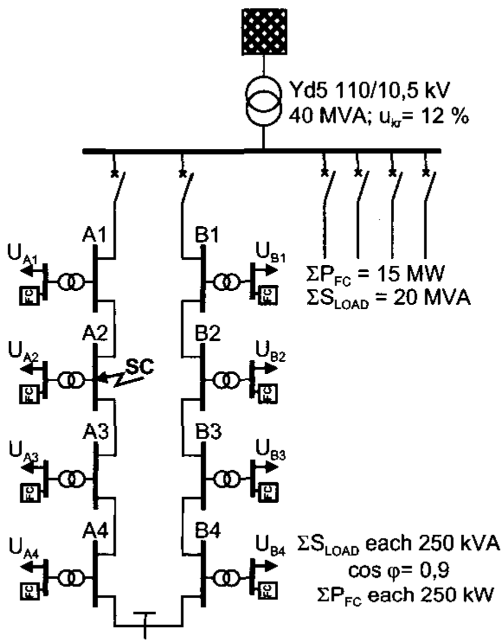

Fig. 6. Single-line diagram of medium-voltage model network corresponding to figure 7

Present guidelines recommend instantaneous tripping (i.e. maximally 200 ms), if voltage at point of common coupling drops below 0.8 p.u. [6]. The overcurrent-time protection relay at faulted feeder trips here after 500 ms and disconnects medium-voltage feeder A. Short-circuits on medium-voltage networks may affect a huge number of dispersed generators on subordinated networks and may result in a loss of dispersed power generation. Selectivity may be achieved by delaying the tripping of undervoltage protection relay's of fuel cells longer than tripping time of feeder protection, if inverter of fuel cell remains synchronized with power system. Simultaneously, uncontrolled and unintended isolated operation of a network area by dispersed generators must be avoided to ensure safety and prevent from out of step reclosing.

Non-directional overcurrent protection relay's of feeders are not affected by fuel cells due to low short-circuit currents of fuel cells. But fuel cells may cause reverse currents through directional protection relay's, like meshed network master relay's at distribution transformers of meshed low-voltage network. Set-point values of tripping current in reverse direction have to be higher than operating current to enable power flow to medium-voltage network.

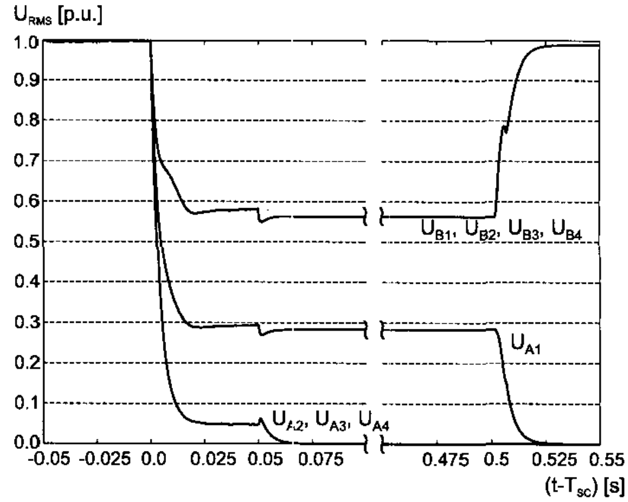

Fig. 7. RMS-Voltages at low-voltage side of distribution transformers

III. Supplying Micro-Grids with Fuel Cells

A. *Conception of a micro-grid*

A micro-grid is a small isolated network with the purpose to supply loads at remote, undeveloped areas or during temporary disconnection from power system. Main characteristics of micro-grids are low short-circuit power and higher fluctuations of load demand [9]. A micro-grid may be supplied by just one fuel cell or by fuel cells in conjunction with electrical energy storage, like capacitors or batteries. Services of power system, like voltage and frequency stability, have to be provided by a fuel cell or electrical energy storage.

Rating of fuel cell is based on peak load demand, if one fuel cell supplies a micro-grid. Change of power output of fuel cell has to meet load variation. Hence hydrogen has to be supplied from storage. Fuel cells supplying micro-grids have to be overrated to ensure an acceptable power quality. Batteries or capacitors can support fuel cell during short-time overload and hence a reduction of rating of fuel cell is possible [10]. Peak load are supplied by both fuel cell and electrical energy storage. Electrical energy storage may be used to smooth load characteristic.

The examined micro-grid is shown at figure 8. It is simulated as a radial network. Star-point of inverter-transformer of fuel cell is direct grounded (TN-C-system). A fuel cell with rated power of 50 kVA supplies the micro-grid. The loads are a resistive load with 5 kW, a resistive-inductive load with 5 kVA and a power factor of 0.95. Furthermore two induction motors with a rating of 5.5 kW and 3.7 kW for continuous duty are simulated. The applied load torque at the induction machines represent a compressor or a pump, that means a square-law load torque depending on revolution of motor [11]. The micro-grid may be operated in parallel with power system or isolated.

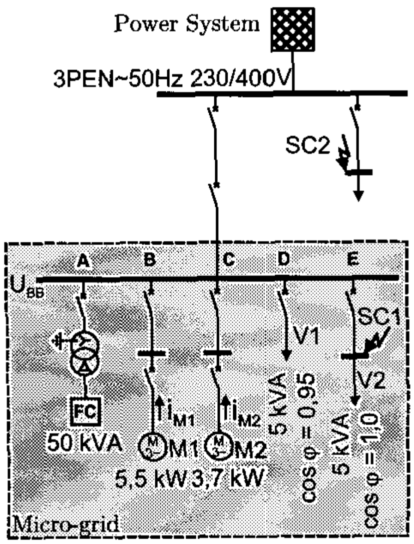

Fig. 8. Single-line diagram of examined micro-grid corresponding to figures 9, 10 and 11

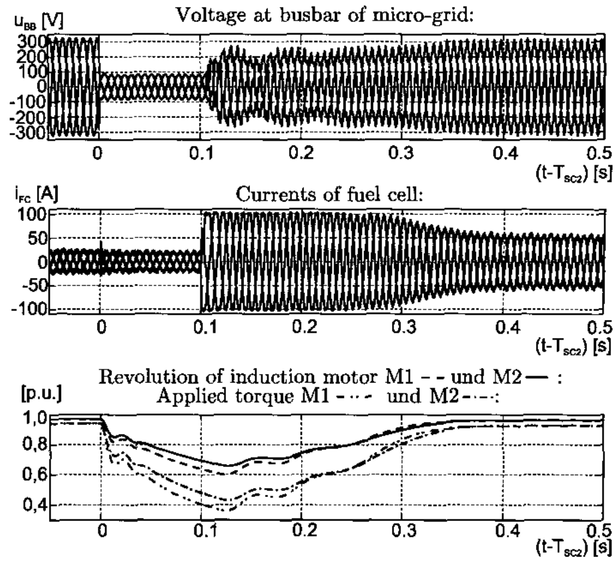

Fig. 9. Disconnection of micro-grid with induction motors due to remote three-phase short-circuit at power system

B. Disconnection from power system

Disconnection from parallel operation with power system during short-circuits on network side has to carried out fast to reduce voltage drop at micro-grid. Especially, if induction motors are running at micro-grid, re-acceleration may cause voltage disturbances after disconnection from power system. Figure 9 shows results of a simulation. The micro-grid was connected to power system, when a remote three-phase short circuit occurs at power system at time T_{SC2}(fault location SC2). Voltage at point of common coupling drops to 25% of nominal voltage. The micro-grid is disconnected from power system after 100 ms. The control of fuel cell changes from current control to voltage-frequency control. Revolutions of induction motors are decreased to 60% - 70% during voltage dip. Re-acceleration of induction motors take about 200 to 250 ms. Voltage of micro-grid is disturbed during re-acceleration period.

C. Start-up of induction motor

Start-up of induction motors take longer due to limited power output of fuel cell inverter. Figure 10 illustrates start-up of the two induction motors at examined micro-grid. Induction motor M1 is started at time T_{M1}. Voltage at main busbar of micro-grid is reduced until induction motor M1 runs at basic speed. Induction motor M2 is started after 400 ms and voltage at main busbar decreases as well. Due to reduced voltage, induction motor M1 needs more current and start-up time of induction motor M2 increases to 500 ms. Both induction motors accelerate between 250 ms and 300 ms at network connection.

D. Short-circuit performance

Short-time overload capacity is limited by current carrying capacity of inverter valves of fuel cell inverter and stored

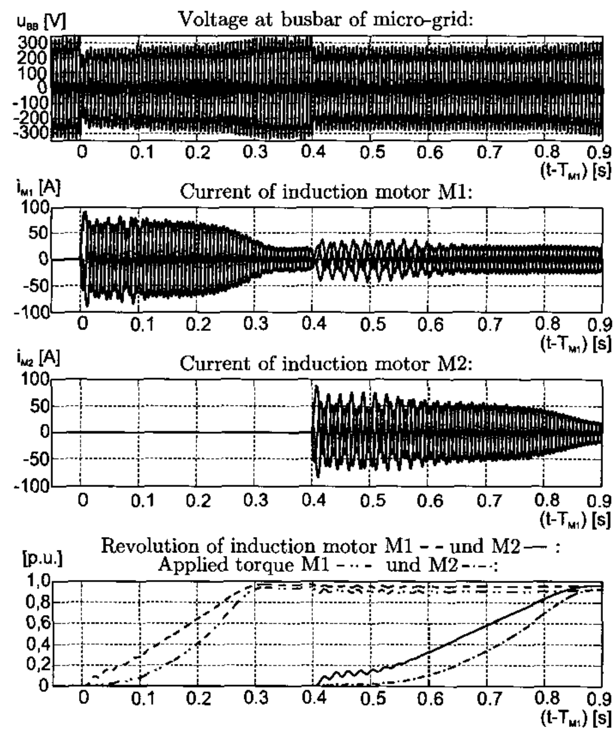

Fig. 10. Acceleration of induction motors at micro-grid

energy of d.c. link capacitor. Hence short-circuit power of micro-grid is low and this leads to low tripping currents during short-circuit. Fuel cell acts as voltage source, due to voltage-frequency control, until maximum permissible current of inverter is reached and limited. Hence current limitation of inverter determine short-circuit current. If inverter of fuel cell is connected directly to micro-grid (without an inverter-transformer), short-circuit current equals maximum permissible current of inverter. Setting of protection scheme has to be based on maximum permissible current of inverter.

If fuel cell inverter feeds via an inverter-transformer to micro-grid, short-circuit current may be different from maximum permissible current of inverter, since current is limited on inverter side of inverter-transformer. Transformation ratio is to consider as well as vector group of inverter-transformer. Figure 11 shows results of simulations with delta-star inverter-transformer of fuel cell. Delta winding is on inverter side and currents are limited to 102 A. The transformation ratio is set to one. A short-circuit at fault location SC1 occurs at time T_{SC1}. Single-phase-to-earth and two-phase-to-earth short-circuits leads to highest currents at micro-grid. Transformed current on micro-grid is $\sqrt{3}$ times the maximum permissible current of inverter, due to delta-star inverter-transformer. Minimum short-circuit current of micro-grid is phase-to-phase clear of earth short-circuit current. It reaches only 86.6% of maximum permissible current of inverter and setting of protection scheme has to be based on that value.

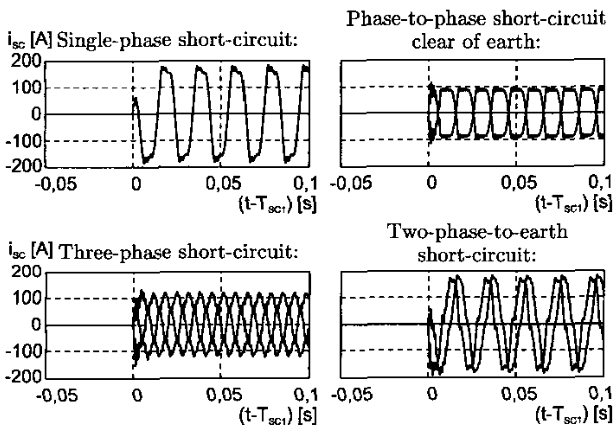

Fig. 11. Short-circuit performance of micro-grid

In case of occasional isolated operation of a micro-grid, tripping range of protection relays have to guarantee the same selectivity in a micro-grid as in connection with power system. Selectivity within the micro-grid is difficult to achieve by using conventional over-current feeder protection [4]. Over-current feeder protection may be sufficient, if operating current splits between several feeder and hence tripping current of feeder protection is lower than current output of fuel cell. Over-current protection is not suitable for main busbar protection of micro-grid. Main busbar can be protected by current differential protection. Protection of main busbar should be integrated into control of fuel cell in order to shut down fuel cell at fault on main busbar. Undervoltage protection relay of fuel cell has to be delayed and used as back-up protection of micro-grid during isolated operation. Induction motors increases peak short-circuit current, but have to be re-accelerated after short-circuit [12].

IV. Conclusions

Power injection into power system is limited by voltage-variation due to functional switching of a single unit, the upper limit of the voltage range for all distributed generators and current carrying capacity of the devices. Non-directional overcurrent protection of feeders are not affected by fuel cells. Exceptions are fuel cells with direct grounded inverter transformer, where tripping of overcurrent protection at point of common coupling is possible due to high zero-sequence currents during unsymmetrical faults to earth. Directional protection relay's have to allow operating current in reverse direction to prevent from false tripping. Voltage sag during a short-circuit may trip undervoltage protection relay's of fuel cells at faultless feeders, if tripping time of feeder protection is longer than tripping time of undervoltage protection relay. Hence selectivity is only achieved by delaying tripping of undervoltage protection relay's until faulted feeder is disconnected, if possible.

Voltage and frequency at an isolated micro-grid is set by a fuel cell or an electrical energy storage. Disconnection from power system has to carried out fast to reduce voltage disturbances at micro-grid. Main characteristic of a micro-grid supplied by fuel cells is low short-circuit power. Hence start-up of induction motor may takes longer and voltage disturbances may occur during acceleration. Setting of protection scheme has to consider inverter-transformer, since minimum short-circuit current may be lower than current limiting of inverter of fuel cell.

Technical problems with integration of fuel cells into power system and micro-grids are solvable. Fuel cells have to prove reliability, availability and economic efficiency, before they take on important tasks of electrical power supply.

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