ADAPTIVE NETWORK PROTECTION IN MICROGRIDS

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Keywords: Microgrids; adaptive protection; distributed energy resources; islanded operation; relay settings; directional interlock

ABSTRACT

Microgrids comprise low voltage distribution systems with distributed energy resources (DER) and controllable loads which can operate connected to the medium voltage grid or islanded in a controlled coordinated way. This concept aims to move from “connect and forget” philosophy towards an integration of DER. Microgrids are expected to provide environmental and economic benefits for end-customers, utilities and society. However, their implementation poses great technical challenges, such as a protection of microgrid. Local generation in a combination with a possible islanded operation can pose protection sensitivity and selectivity problems in case of fault depending on the relay settings.

This paper presents a novel adaptive microgrid protection system using digital relaying and advanced communication. The protection system is based on a centralized architecture where relay protection settings are modified centrally with regard to a microgrid operating condition.

1 INTRODUCTION

Power systems currently undergo considerable change in operating requirements – mainly as a result of deregulation and due to an increasing amount of distributed energy resources (DER). In many cases DER include different technologies that allow generation in small scale (micro-sources) and some of them take advantage of renewable energy resources (RES) such as solar, wind or hydro energy. Having micro-sources close to the load has the advantage of reducing transmission losses as well as preventing network congestions. Moreover, the chance of having a power supply interruption of end-customers connected to a low voltage (LV) distribution grid is diminished since adjacent micro-sources, controllable loads and energy storage systems can operate in the islanded mode in case of severe system disturbances on the transmission system level (in fact a power delivery can be fully independent of the state of the main grid). This is known today as a microgrid [1, 2] and is depicted in Figure 1 where the microgrid is connected to the main medium voltage (MV) grid when the circuit breaker 1 (CB1) is closed (the circuit breakers CB3.2 and 6.2 are normally open). Microgrids may potentially offer various advantages to end-consumers, utilities and society, such as:

- Improved energy efficiency
- Minimized overall energy consumption
- Reduced greenhouse gases and pollutant emissions
- Improved service quality and reliability
- Cost efficient electricity infrastructure replacement

In light of these, the microgrid concept has stimulated many researchers and attracted the attention of governmental organizations in Europe, USA and Japan [3-5]. Nevertheless, there are various technical issues associated with the integration and operation of microgrids. One of the major challenges is a protection system for microgrid which must respond to both main grid and microgrid faults. In the first case the protection system should isolate the microgrid from the main grid as rapidly as necessary to protect the microgrid loads. In the second case the protection system should isolate the smallest part of the microgrid when clears the fault [6]. A segmentation of microgrid, i.e. a creation of multiple islands or sub-microgrids must be supported by micro-source and load controllers. Under these circumstances, problems related to selectivity (false, unnecessary tripping) and sensitivity (undetected faults or delayed tripping) of protection system may arise.

Issues related to a protection of microgrids and distribution grids with a large penetration of DER have been addressed in recent publications [7-10]. Basically, there are two main issues, first is related to a number of installed micro-sources in the microgrid and second is related to an availability of a sufficient level of short-circuit current in the islanded operating mode of microgrid since this level may drop down substantially after a disconnection from the stiff medium voltage grid.

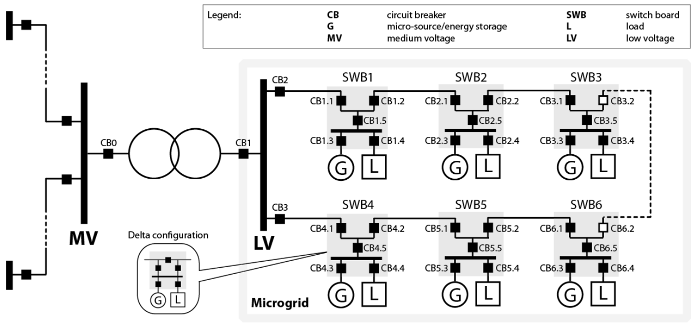

Figure 1: *Typical microgrid layout.*

In [11], authors have made short-circuit current calculations for a radial feeder with DER and observed that short-circuit currents, which are used in over-current (OC) protection relays, depend on the connection point of and the feed-in power of DER. Because of these directions and amplitudes of short circuit currents will vary. In fact, operating conditions of microgrid are constantly changing because of the intermittent micro-sources (wind and solar) and periodic load variation. Also a network topology can be regularly changed aimed at loss minimization or achievement of other economic or operational targets. In addition controllable islands of different size and content can be formed as a result of faults in the main grid or inside a microgrid. In such circumstances a loss of relay coordination may happen and generic OC protection with a single setting group may become inadequate, i.e. it will not guarantee a selective operation for all possible faults. Therefore, it is essential to ensure that settings chosen for OC protection relays take into account a grid topology and changes in location, type and amount of generation. Otherwise, unwanted operation or failure to operate when required may occur. In order to cope with bi-directional power flows and low short-circuit current levels in microgrids dominated by micro-sources with power electronic interfaces a new protection philosophy is required, where setting parameters of relays must be checked/updated periodically to ensure that they are still appropriate.

This paper presents a novel adaptive microgrid protection concept using advanced communication system, real-time measurements and data from off-line short circuit analysis. This concept is based on an adaptation of protection relay settings with regard to a microgrid state (topology, generation and load). Further, on the hardware realization (basic components, communication, etc.) of this concept and numerically simulated test results are presented.

The outlay of this paper is as follows, Section 2 gives an overview of major protection issues in microgrids. Section 3 illustrates a novel adaptive protection concept for microgrids, followed by a discussion of the simulated results in Section 4. Section 5 provides conclusions.

2 PROTECTION ISSUES IN MICROGRIDS

A protection of low voltage distribution grid where feeders are radial with loads tapped-off along feeder sections is usually designed assuming an unidirectional power flow and is based on OC relays with time-current discriminating capabilities. OC protection detects the fault from a high value of the fault current flowing downwards. In modern digital relays, a tripping short-circuit current can be set for a wide range, e.g. 0.6-15*CB rated current. If a measured current is above the tripping setting, the relay operates to trip the CB on the line with a short delay defined by a coordination study and compatible with a locking strategy used (no locking, fixed hierarchical locking, directional hierarchical locking).

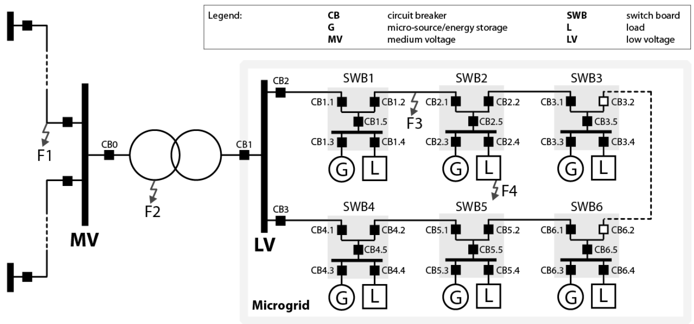

Figure 2: *Different fault scenarios in microgrid.*

During the last decade, the classical set up in distribution grids has slowly been changing due to the installation of DERs such as photovoltaic (PV) panels, wind and micro-gas turbines, fuel cells, batteries, etc. Most of the micro-sources and energy storage devices are not suitable for supplying power directly to the grid and have to be interfaced to the grid with power electronics (PE) interfaces. A use of PE interfaces leads to a number of challenges in microgrid protection, especially in the islanded mode.

Figure 2 represents the same microgrid as shown in Figure 1 with two feeders connected to the LV bus and to the MV bus via a distribution transformer. Each feeder has three switchboards (SWB). Each SWB has star or delta configuration and connects the local DER and load to the feeder. We analyzed two external (F1, F2) and two internal (F3, F4) microgrid faults. All LV CBs (from CB1 to CB6.5) may have different ratings but are equipped with OC protection and used for segmenting the microgrid. In general, protection issues in the microgrid can be divided in to two groups with regard to the microgrid operating state, see Table 1. It also point out the importance of the "3S" (sensitivity, selectivity and speed) requirements for different cases, which provides a basis for the design criteria for the microgrid protection system.

2.1 Grid connected – external fault (F1, F2)

In case of fault F1 a main grid (MV) protection clears the fault. If sensitive loads are presented in microgrid, the microgrid could be isolated by CB1 as fast as in 70 ms (depending on a voltage drop in the microgrid). Also the microgrid must also be isolated from the main grid by CB1 in case of no protection units tripping in medium voltage.

Table 1: Major classes of microgrid protection problems

Operating mode	*Fault location*			
	External faults (main grid)		*Internal faults (microgrid)*	
	MV feeder, bus-bar (F1)	*Distribution transformer (F2)*	*LV feeder (F3)*	*LV consumer (F4)*
Grid connected (CB1 is closed)	Fault is normally managed by MV system. Microgrid isolation by CB1 in case of no MV protection tripping. Possible fault sensitivity problems for CB1*.	Fault is normally managed by MV system (CB0). CB1 is opened by "follow-me" function of CB0. In case if communication fails then possible fault sensitivity problem for CB1*.	Disconnect a smallest portion of microgrid (CB1.2 and CB2.1). CB1.2 is opened by fault current from the grid (high level). Low level of a reversed fault current from feeder's end may cause sensitivity problems for CB2.1*. In this case a "follow-me" function of CB1.2 can to open CB2.1. In case if communication fails then possible fault sensitivity problems for CB2.1*.	Faulty load is isolated by CB2.4 or fuse. In case of no tripping the SWB is isolated by CB2.5 and local DER is cut-off. No sensitivity or selectivity problems.
Islanded (CB1 is open)	---	---	Disconnect the smallest portion of microgrid (CB1.2 and CB2.1). Low level of fault currents from both directions may cause sensitivity problems for CB1.2 and CB2.1*.	Faulty load is isolated by CB2.4 or fuse. In case of no tripping the SWB is isolated by CB2.5 and local DER is cut-off. Sensitivity or selectivity problems not likely.

*) low fault current contribution from the Microgrid in case of DER with PE interfaces.

A detection of F1 with a generic OC relay can be problematic in the case when most of micro-sources in the microgrid are connected by means of PE interfaces having built-in fault current limitation, i.e. there is no significant rise in current passing through CB1. Typically they are capable of supplying 1.1-1.2*$I_{DERrated}$ to a fault, unless the converters are specifically designed to provide high fault currents. These numbers are much lower than a short-circuit current supplied by the main grid. A directional OC relay acting on CB1 is a feasible solution only if the current is used for the fault detection. In order to increase relay sensitivity a setting for a reverse current is defined as a sum of fault current contributions from all connected DERs (1). This value will vary in case of a large number of different types of DERs. Thus, the setting has to be continuously monitored and adapted when microgrid generation undergoes considerable changes (related to the number and type of connected DERs). Alternatively, voltage drop (magnitude and duration) or/and system frequency (instantaneous value and rate of change) can be used as another indicators for a tripping of CB1 [12]. Some distribution network operators (DNO) may require microgrid to stay connected and supply reactive power to the fault for up to several seconds.

In case of fault F2 a distribution transformer OC protection clears the fault by opening CB0. CB1 is opened simultaneously by “follow-me” function (hardware lock) of CB0. In case of hardware lock failure a possible fault sensitivity problem can arise as in the case of fault F1. Typical solutions are similar to the F1 case, such as directional adaptive OC protection, under-voltage and under-frequency protection.

2.2 Grid connected – fault in the microgrid (F3)

In case of fault F3 a microgrid protection should disconnect the smallest possible portion of the LV feeder by CB1.2 and CB2.1. CB1.2 is opened due to a high level of short-circuit current supplied by the main MV grid. If CB1.2 fails to trip, the fault F3 must be cleared by CB1.1 which is a backup protection for CB1.2. However, the sensitivity of OC protection relay in CB1.1 can be potentially disturbed in the case when synchronous DERs (e.g. diesel generator) are installed and switched-on in SWB1 (i.e. between CB1.1 and the fault F3). In this case the fault current passing the CB1.1 with a DER will be smaller than in case without a DER. This effect is known as protection blinding (the larger the synchronous DER the greater is the effect) and may result in a delayed CB1.1 tripping because of the fault current transition from a definite-time part to an inverse-time part of relay tripping characteristic. The delayed fault tripping will lead to an unnecessary disconnection of local synchronous DERs (usually low power diesel generators have very low inertia and can lose synchronism if fault clearing too slow). However, this issue can be solved by a proper coordination of the microgrid and the DER protection systems. Another option is adapting protection settings with regard to the current operating conditions (DER status). If, as likely, CB1.2 operates faster than CB2.1 it will island a part of the microgrid which will be connected to the fault F3. If it is possible to balance a generation and load in the islanded segment of the microgrid it is expedient to isolate that group of micro-sources and loads from the fault F3 by opening CB2.1 and possibly closing CB3.2-6.2. However, a reversed and low level short circuit current in case of DERs with PE interfaces will cause a sensitivity problem for CB2.1 similar to one described in Section 2.1 in case of the fault F1. Possible solutions include directional adaptive OC protection and a “follow-me” function of CB1.2 which opens CB2.1 (in case of communication failure possible sensitivity problems for CB2.1).

2.3 Grid connected – fault in the end-consumer site (F4)

In case of fault F4 a high short-circuit current is supplied to the fault from the main grid together with a contribution from DER and will lead to a tripping of CB2.4. Frequently, there is a fuse instead of CB which is rated in such a way that a shortest possible fault isolation time is guaranteed. In case of no tripping the SWB2 is isolated by CB2.5 and local DER is cut-off. No sensitivity or selectivity problems are foreseen in this scenario.

2.4 Islanded mode – fault in the microgrid (F3)

The microgrid operates in the islanded mode when it is intentionally disconnected from the main MV grid by CB1 (full microgrid) or any CB along the LV feeder (a segment of the microgrid). This operating mode is characterized by an absence of a high level of short-circuit current supplied by the main grid. Generic OC relays would be required to be replaced by directional OC relays because fault currents flow from both directions to the fault F3. If CB1.2 and CB2.1 use setting groups chosen for the grid connected mode they will have a selectivity problem to detect the fault F3 and trip within acceptable time frame in case of DER with PE interfaces; the fault current could shift from a definite-time part to an inverse-time part of the relay tripping characteristic. The question arises: why one needs to care about a fault if there is no fault current? The answer to this question is (a) for safety reasons (b) to avoid damage to equipment caused by permanent faults which may propagate. There are two possible ways to address the problem of absence of a high level short-circuit current:

- Install a source of high short-circuit current (e.g. a flywheel or a super-capacitor) to trip CBs/blow fuses with settings/ratings for the grid connected mode. However, a short-circuit handling capability of PE interfaces can be increased by increasing the respective overloading rating which leads to extra investment cost. In case such source of high short-circuit current is installed, it would be typically connected to the LV bus bar.
- Install an adaptive microgrid protection using on-line data on microgrid topology and status of available micro-sources/loads.

2.5 Islanded mode – fault in the end-consumer site (F4)

In case of fault F4, a low short-circuit current is supplied to the fault from the local DERs. There is no grid contribution. However, CB2.4 settings selected for the main grid connected mode are just slightly higher than rated load current. It assures that the end-customer site will be disconnected even if only DERs with PE interfaces are available in the microgrid. In case of no tripping the SWB2 must be isolated by CB2.5 using directional OC relay. Similar to the grid connected mode there are no sensitivity or selectivity problems are foreseen in the islanded mode for the fault in the end-consumer site.

2.6 Conclusive remarks

Finally it was seen that the main microgrid protection problem is related to a large difference between fault currents in main grid connected and islanded modes. A microgrid protection system must have a high sensitivity to faults and selectively isolate/sectionalize microgrid especially in the case of DERs with PE interfaces (low fault current levels). In fact a decision on either sectionalize microgrid or shut it down in case of fault will depend on needs of microgrid customers and whether a cost involved (protection and communication) could be justified for benefits gained by a sectionalizing (e.g. reduced end-consumer interruption time). According to system reliability index figures, approximately 20-40 faults (overhead lines) and <5 (underground cables) per 100 km occur annually in typical European LV networks [13]. It implies that, taking into account the on the connections faults, less than 2 faults per 5 years (overhead lines) and 1 fault per 20 years (underground cables) will take place inside a typical microgrid spanning over 1 km. However, more faults happen in MV grid and microgrid has to be isolated from these faults too.

3 ADAPTIVE PROTECTION FOR MICROGRID

This section illustrates an adaptive protection system that can potentially solve problems identified in the previous section by anticipating an impact of micro-sources (DERs) and microgrid configuration on the relay performance and accordingly change the relay settings to ensure that the whole microgrid is protected at all times. Adaptive protection is as "an online activity that modifies the preferred protective response to a change in system conditions or requirements in a timely manner by means of externally generated signals or control action" [14]. Technical requirements and suggestions for a practical implementation of an adaptive microgrid protection system are as following:

- Use of numerical directional OC relays because fuses or electro-mechanical and standard solid state relays are (especially for selectivity holding) inapplicable - they do not provide the flexibility for changing the settings of tripping characteristics and they have no current direction sensitivity feature.
- Numerical directional OC relays must dispose of possibility for using different tripping characteristics (several settings groups) that can be parameterized locally or remotely automatically or manually.
- Use of new/existing communication infrastructure (e.g. twisted pair, power line) and standard communication protocols (Modbus, IEC61850) such that individual relays can communicate and exchange information with a central computer or between different individual relays fast[1] and reliably to guarantee a required application performance.

An adaptive protection system which will satisfy these requirements will be characterized by a relatively high investment cost in comparison to a conventional protection system based on fuses. In light of this it is interesting to carry out a separate

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[1] The communication time lag and the maximum time lag are not critical values for this application, because the communication infrastructure is used to collect information about the microgrid configuration and to change accordingly relay settings only. The interlock, if required, is done by means of physical point-to-point connection. On master-slave protocol like Modbus the changes of the configuration have to be identified with a maximum delay of 1-10 seconds dependent on the dimension of the network, and the protection reconfiguration has to be completed in times of the same order as previous ones, providing that basic backup protection functions are present during the transitory phase. On pear-to-pear protocol like IEC61850 the changes on the network configuration are triggering the protection reconfiguration. The accepted delays are equivalent with the previous ones.

cost-benefit analysis in case of microgrid. Cost will correspond to investment and operating costs over a system lifetime and benefit will correspond to a reduced outage time and opportunity loss. It is not a subject of this study where the focus is on a technical realization of an adaptive protection system for microgrids. An example of centralized adaptive protection system is shown in Figure 3.

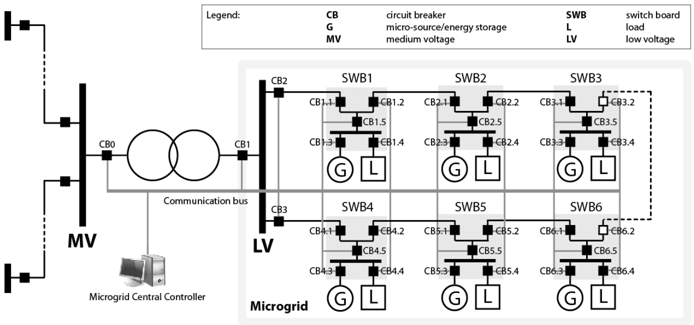

Figure 3: *Centralized adaptive protection system for microgrid.*

There is a microgrid central controller (MCC) and communication system in addition to elements shown in Figure 1. Communication electronics make each CB with an integrated directional OC electronic trip unit (relay) capable of exchanging information with MCC. For example, in Figure 3 CBs are connected to the serial communication bus RS485 and use standard industrial communication protocol Modbus. By polling individual relays the MCC can read data (electrical values, status) from CBs and if necessary modify a subset of the relay settings (tripping characteristics) on the fly without any resetting protection needs.

Each individual relay takes a tripping decision locally (independently of MCC) and performs in accordance to Figure 4.

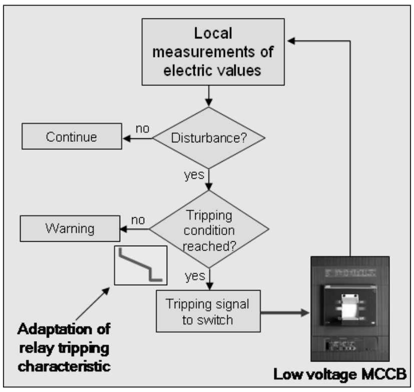

Figure 4: *Local protection function inside circuit breaker.*

In case an abnormal situation is detected a tripping condition is checked (a measured current in a specific direction is compared with the actual relay setting). If the tripping condition is reached a CB is open. The main goal of the adaptive protection system shown in Figure 3 is to maintain settings of each relay with regard to a current state of the microgrid. It is effectuated by a special module in MCC which is responsible for a periodic check and update of relay settings. It consists of two main components:

- Pre-calculated information during off-line fault analysis of a given microgrid
- On-line operating block

3.1 Off-line analysis

A set of meaningful microgrid configurations as well as feeding-in states of DERs (on/off) is created for off-line fault analysis and is called an event table. Each record in the event table has a number of elements equal to a number of monitored CBs in the microgrid (some elements may have higher priority than others, e.g. the central CB which connects LV and MV grids) and is binary encoded, i.e. element=1 if a corresponding CB is closed and 0 if it is open (Figure 5). Next, fault currents passing through all monitored CBs are estimated by simulating short-circuits (3-phase, 2-phase, phase-to-ground, etc.) in different locations of the protected microgrid at a time in accordance with IEC 60909. During repetitive short-circuit calculations a topology or a status of a single DER is modified between iterations. As different fault locations for different microgrid states are processed the results (the magnitude and direction of fault current seen by each relay) are saved in a specific data structure.

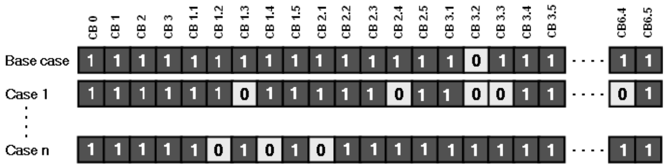

***Figure 5**:* *Structure of event table.*

Based on these results suitable settings for each directional OC relay and for each particular system state are calculated in such a way that guarantees a selective operation of microgrid protection. These settings are grouped into an action table which has the same dimension as the event table. In addition to a regulation of protection settings other actions such as activation of protection function can be done, e.g. a directional interlock can be activated in the islanding situation. The event and action tables are part of the configuration level of the microgrid protection and control system shown in Figure 6, where:

- *External Field Level* represents energy market prices, weather forecast, heuristic strategy directives and other utility information

- *Management Level* includes historic measurements and distribution management system (DMS)
- *Configuration Level* consists of a computer or PLC situated centrally (substation) or locally (switchboard) which is able to detect a system state change and send a required action to hardware level
- *Hardware Level* transmits a required action from the configuration level to on-field devices by means of a communication network. In the case of a large microgrid, this function can be divided between several local controllers which communicate only selected information to the central unit.
- *Protection Level* may include CB status, release settings, interlocking configuration, etc. Together with Real-time Measurements Level they are sitting inside on-field devices.

3.2 On-line operation

During the on-line operation the MCC monitors the microgrid state by polling individual directional OC relays. This process runs periodically or is triggered by an event (tripping of CB, protection alarm, etc.) and uses communication system shown in Figure 3. The microgrid state information received by the MCC is used to construct a status record which has a similar dimension as a single record in the event table.

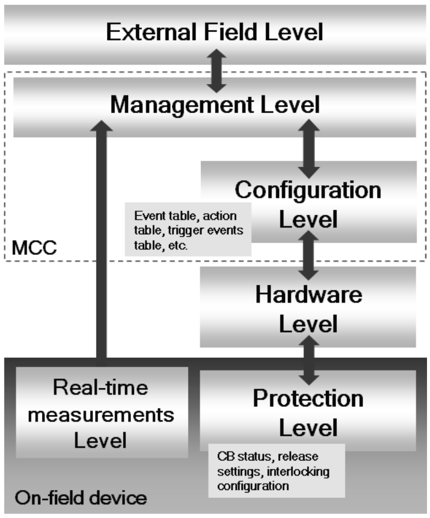

Figure 6: *Microgrid protection and control architecture.*

The status record is used to identify a corresponding entry in the event table. Finally, the algorithm retrieves the pre-calculated relay settings from the corresponding record in the action table and uploads the settings to on-field devices via the communication system. Figure 7 illustrates phases of the adaptive protection algorithm.

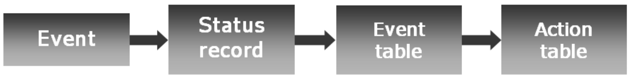

Figure 7: *Phases of on-line adaptive protection algorithm with available look-up tables (the event and action tables).*

3.3 Directional interlock

Fault detection and selective isolation are very challenging tasks in microgrids dominated by DERs with PE interfaces (Table 1). This subsection presents a solution based on extension of the microgrids adaptive protection system with a directional interlock. A non-directional interlock is a well known technique used in radial distribution feeders without DERs [15].

The interlock starts from the end of the feeder towards the supply side and connects an output port of the trip unit to an input port of the trip unit immediately to the supply side by means of a simple screened-twisted-pair cable. In the case of fault, the CB immediately to the supply side sends a locking signal to the hierarchically higher CB and, before intervening, checks that a similar locking signal has not been reached by the CB on the load side. This guarantees a selective operation of relays even where it is not possible to use a current discrimination. However, in a presence of DERs along the feeder the non-directional interlock will not work correctly because the fault can be supplied from both sides and all CBs between the fault and the most remote DER at the end of the feeder will be unnecessarily tripped which makes difficult to detect the fault location

An evolution of this pre-cabled system could be an adaptive directional interlock in order to avoid a non-selective operation of relays in the microgrid. The interlock direction is changed by reassignment output and input ports of corresponding relays. The interlock direction is changed on-fly (in less than 50 ms) depending on a direction of the fault current with regard to a direction of the interlock (towards supply side, i.e. main MV grid) before the fault (Figure 8).

The reassignment of ports is based on the following rules:

if The fault current direction is opposite to the present interlock direction

then Keep present port assignment

and Relay sends locking signal to the present interlock direction

if The fault current direction is similar to the present interlock direction

then switch output/input ports, i.e. interlock direction

And relay sends locking signal to the new interlock direction (opposite to the present interlock direction)

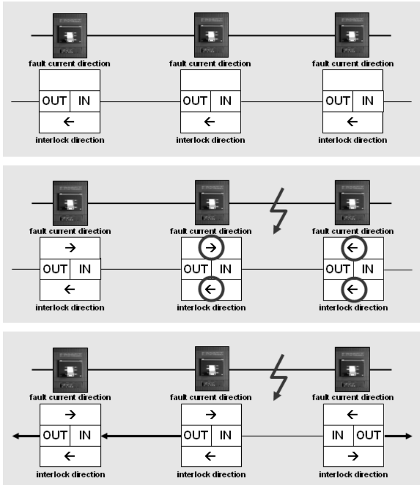

Figure 8: *Adaptive directional interlock.*

Adaptive directional interlock sends the blocking signals in correct directions, i.e. relays on both sides of faulty element will trip and selectively isolate the fault.

4 SIMULATION RESULTS

This section shows an illustrative example of an adaptive protection system combined with a directional interlock and the results are discussed. We used the same microgrid setup as shown in Figure 3. Parameters of the test microgrid are given in Appendix. The microgrid consists of several DERs including synchronous machines and units with PE interfaces. We explored two scenarios with regard to a microgrid configuration and status of DERs:

- Microgrid without DERs in the grid connected mode
- Microgrid with DERs (synchronous machines) in the grid connected and islanded modes

4.1 Microgrid with DERs switched off in the grid mode

The first scenario is shown in Figure 9. This microgrid topology was used as a base case and the first entry in the event table.

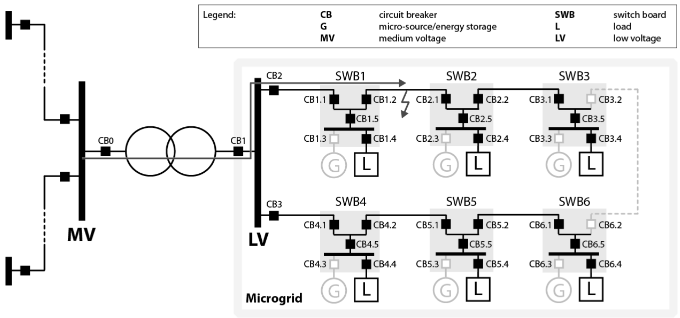

Figure 9: *Scenario A1: microgrid with DERs switched off is connected to a medium voltage distribution grid.*

We assume that each electronic trip circuit breaker has a similar shape of an over-current protection trip curve (Figure 10). The trip curve consists of an inverse time part L (protection against overloads), a constant time delay part S (protection against short circuit with short time delay trip) and an instantaneous part I (instantaneous protection against short circuit). In order to provide a selective operation of circuit breakers we used different time delays t_s in the range between I_{kmin} (expected minimum short circuit current) and I_{kmax} (expected maximum short circuit current). The values of I_{kmin}/I_{kmax} are obtained from the results of off-line numerical simulations of 3-phase, 2-phase, single phase faults in accordance to IEC 60909. The CB1 closest to the source has highest t_s and the most distant CB3.2 and CB6.2 have the lowest t_s (Figure 11). The instantaneous tripping part I is removed from all curves for a simplification purposes.

The microgrid topology and suitable OC protection settings for all CBs (calculated during the off-line fault analysis [17]) in the base case are shown in Table 2 based on Figure 9 and Figure 11. DER and load protection settings do not set here but the information on DER and load status (on/off) is required for a correct operation of the microgrid adaptive protection.

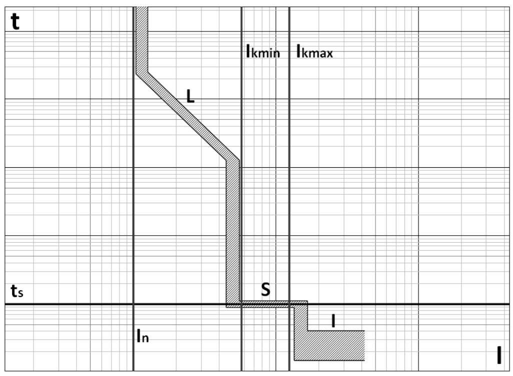

Figure 10: *Typical time-current curve for a low voltage electronic trip circuit breaker [15].*

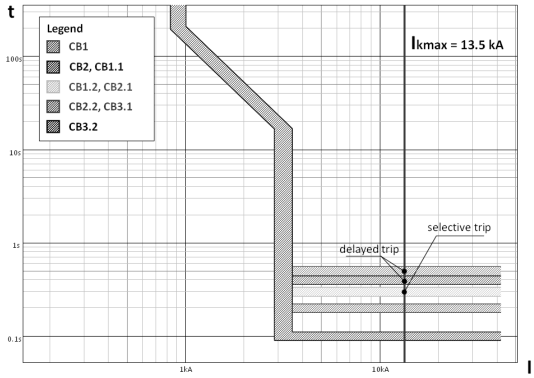

Figure 11: *Trip curves for circuit breakers in the upper feeder (identical for CBs in the lower feeder) in the base case and a tripping sequence in Scenario A1 (Figure 9).*

Table 2: Scenario A1: Status of Circuit Breakers 1=close, 0=open and Over-current Protection Settings t_s in Seconds. Black Box and Bold Numbers Show CBs that See the Fault

Upper feeder	CB1	CB2	CB1.1	CB1.2	CB2.1	CB2.2	CB3.1	CB3.2	
	1	1	1	1	1	1	1	0	
	0.5	**0.4**	**0.4**	**0.3**	0.3	0.2	0.2	0.1	
Lower feeder		CB3	CB4.1	CB4.2	CB5.1	CB5.2	CB6.1	CB6.2	
		1	1	1	1	1	1	0	
		0.4	0.4	0.3	0.3	0.2	0.2	0.1	
DER + load	CB1.3	CB1.4	CB1.5	CB2.3	CB2.4	CB2.5	CB3.3	CB3.4	CB3.5
	0	1	1	0	1	1	0	1	1
DER + load	CB4.3	CB4.4	CB4.5	CB5.3	CB5.4	CB5.5	CB6.3	CB6.4	CB6.5
	0	1	1	0	1	1	0	1	1

In case of fault in the cable between SWB1 and SWB2 (Figure 9) all CBs between the fault and the LV busbar see the fault supplied by the main MV grid (black box and bold numbers in Table 2), but only CB1.2 will trip after t_s=300 ms (Figure 11) and CB2.1 will be opened by the "follow-me" function of CB1.2 in order to avoid connecting the fault to the healthy feeder by closing CB3.2 and CB6.2. Other CBs that see the fault are delayed (in absence of a logic discrimination auxiliary connection). However, this method is limited by a number of discriminating time steps (t_s is recommended to be less than 800 ms) and is only suitable for feeders with a small number of switchboards.

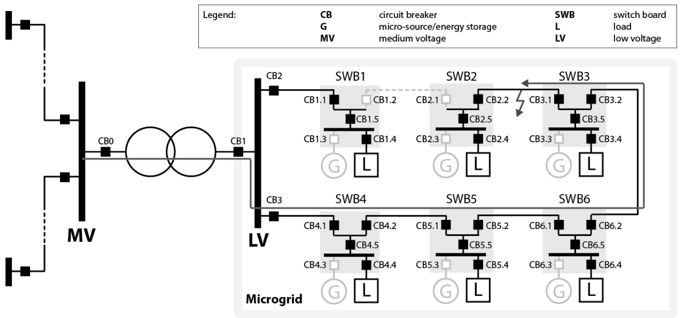

Figure 12: *Scenario A2: microgrid with all DERs switched off is connected to the medium voltage distribution grid.*

Assume SWB2 and SWB3 are re-supplied via SWB6 (CB3.2 and CB6.2 are closed) after the fault between SWB1 and SWB2 is selectively eliminated (CB1.2 and CB2.1 are open). A selectivity problem may appear if using base case protection settings from Table 2. For example, if the second fault will appear between SWB2 and SWB3 (Figure 12) it will be eliminated by CB3.2 and CB6.2 (t_s=100ms) instead of CB3.1 (t_s=200 ms) and the load in SWB3 will be unnecessarily tripped.

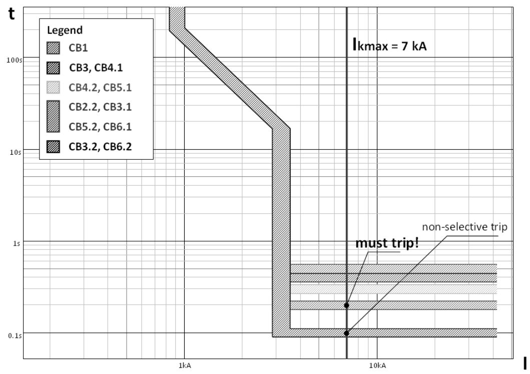

Figure 13: *Base case trip curves and a tripping sequence in Scenario A2 with non-directional OC protection (Figure 12).*

Selectivity can be improved by:

- Applying directional OC relays
- Modification of protection settings of non-directional OC relays

In the first case we would need to install a new hardware. Each relay will have two t_s settings, one for each direction (clockwise and counter-clockwise) as shown in Table 3. In this case a selective protection operation is guaranteed (Figure 14) and SWB3 will remain connected after the fault is eliminated.

Table 3: Scenario A2: CB Status and Directional OC Protection Settings t_s

Upper feeder		CB1	CB2	CB1.1	CB1.2	CB2.1	CB2.2	CB3.1	CB3.2
		1	1	1	0	0	1	1	1
	→	**0.8**	0.7	0.7	0.6	0.6	0.5	0.5	0.4
	←		0.1	0.1	0.2	0.2	0.3	**0.3**	**0.4**
Lower feeder			CB3	CB4.1	CB4.2	CB5.1	CB5.2	CB6.1	CB6.2
			1	1	1	1	1	1	1
	→		**0.7**	**0.7**	**0.6**	**0.6**	**0.5**	**0.5**	**0.4**
	←		0.1	0.1	0.2	0.2	0.3	0.3	0.4
DER + load	CB1.3	CB1.4	CB1.5	CB2.3	CB2.4	CB2.5	CB3.3	CB3.4	CB3.5
	0	1	1	0	1	1	0	1	1
DER + load	CB4.3	CB4.4	CB4.5	CB5.3	CB5.4	CB5.5	CB6.3	CB6.4	CB6.5
	0	1	1	0	1	1	0	1	1

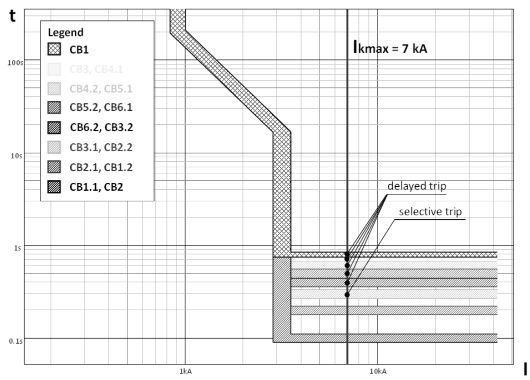

Figure 14: *Base case trip curves and a tripping sequence in Scenario A2 with directional OC protection (Figure 12).*

In the second case we modify S part of the base case trip curves by adjusting t_s settings (Figure 15). A second record in the event and action tables is created during the off-line fault analysis. In particular we can observe lower t_s for CB2.2 and CB3.1 and higher t_s for CB3.2 and CB6.2 in comparison to the values shown in Table 2. The second solution with t_s modification is characterized by more narrow range of time delays. The maximum t_s=0.6 s versus 0.8 s in case of directional OC protection.

Table 4: Scenario A2: CB Status and Modified OC Protection Settings t_s

Upper feeder	**CB1**	**CB2**	**CB1.1**	**CB1.2**	**CB2.1**	**CB2.2**	**CB3.1**	**CB3.2**	
	1	1	1	0	0	1	1	1	
	0.6	0.3	0.3	0.2	0.2	0.1	**0.1**	**0.2**	
Lower feeder		**CB3**	**CB4.1**	**CB4.2**	**CB5.1**	**CB5.2**	**CB6.1**	**CB6.2**	
		1	1	1	1	0	1	1	
		0.5	**0.5**	**0.4**	**0.4**	**0.3**	**0.3**	**0.2**	
DER + load	**CB1.3**	**CB1.4**	**CB1.5**	**CB2.3**	**CB2.4**	**CB2.5**	**CB3.3**	**CB3.4**	**CB3.5**

	0	1	1	0	1	1	0	1	1
DER + load	**CB4.3**	**CB4.4**	**CB4.5**	**CB5.3**	**CB5.4**	**CB5.5**	**CB6.3**	**CB6.4**	**CB6.5**
	0	1	1	0	1	1	0	1	1

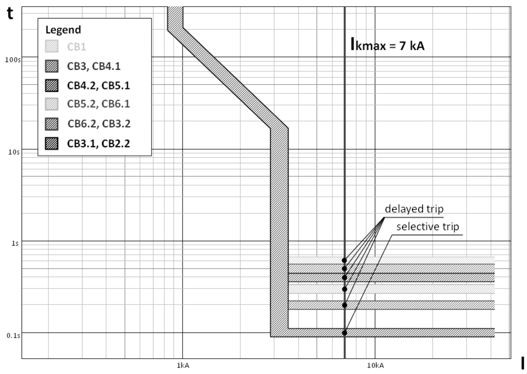

Figure 15: *Modified base case trip curves (t_s settings) and a tripping sequence in Scenario A2 with non-directional OC protection (Figure 12).*

4.2 Microgrid with DERs switched on in the grid and islanded modes

Assume there is a considerable change in the microgrid configuration and status of DER units: the cable between SWB4 and SWB5 is disconnected for a maintenance work and SWB5 and SWB6 are supplied via SWB3 (CB3.2 and CB6.2 are closed) as illustrated in Figure 16.

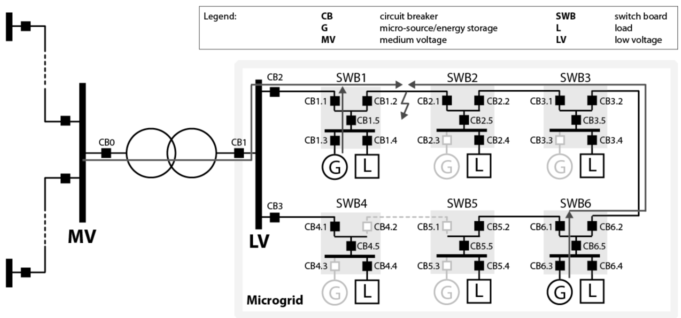

Figure 16: *Scenario B1: microgrid with synchronous DERs switched on is connected to the medium voltage distribution grid.*

Two identical synchronous diesel generators (parameters are given in Appendix) are connected in SWB1 and SWB6. In addition we assume that all non-directional OC protection relays use t_s settings from the base case shown in Table 2.

In case of fault between SWB1 and SWB2 (Figure 16) there is no problem to detect and selectively isolate the fault from the main grid side by CB1.2, also because the fault current seen by CB1.2 becomes higher I_{kmax} = 15 kA vs. 13.5 kA in the base case due to a contribution from the synchronous DER in SWB1. The fault current supplied by the second DER in SWB6 and seen by CB2.1 is 2 kA. It can only activate the L part of the relay's trip curve with the expected tripping time delay of 40 s. Therefore, CB2.1 is opened by the "follow-me" function of CB1.2 and isolates the fault from the LV feeder side in t_s=300 ms (if using directional OC protection then t_s=600 ms, see Table 3).

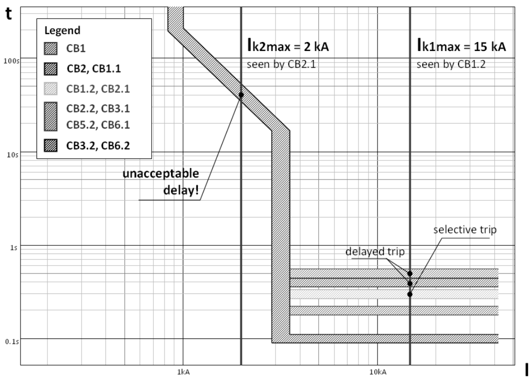

Figure 17: *Base case trip curves and a tripping sequence in Scenario B1 with directional OC protection (Figure 16).*

The main concern is $t_s \geq 300$ ms set for the OC relay in CB1.2 which may affect a stability of the synchronous DER with a small inertia in SWB1. A preferred solution is based on the adaptive directional interlock (Section 3.3). The time delay t_s is set at 100 ms for all OC relays in the microgrid. Then blocking signals are sent in correct directions which prevents an unnecessarily disconnection of DERs and healthy parts of the microgrid.

Next we assume that after an isolation of the first fault the island which includes SWB2, 3, 5 and 6 is formed as shown in Figure 18. The synchronous DER in SWB6 is switched to a frequency control mode and additionally each load in the island is dropped from 100A to 50A. Assume there is a second fault inside the islanded microgrid between SWB2 and SWB3 and all non-directional OC relays use t_s settings from the base case shown in Table 2. Ideally, the fault should be cleared by CB2.2 and CB3.1. CB2.2 can not trip since there is no fault current source in SWB2, but it can be opened by the "follow-me" function of CB3.1. The t_s of CB3.1 is set at 200 ms for a minimum fault current level of 4*In CB = 3.2 kA. In case of using directional OC protection (Table 3) t_s = 300 ms for CB3.1.

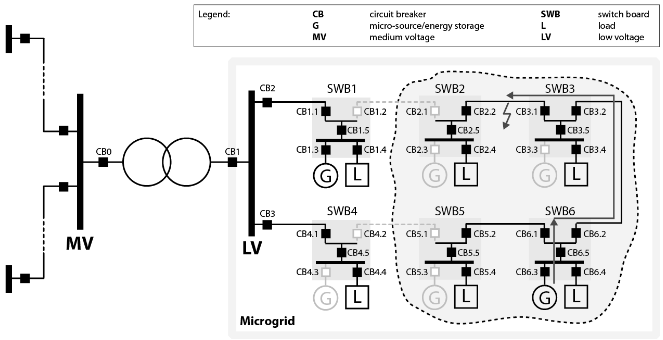

Figure 18: *Scenario B2: islanded microgrid with the synchronous DER.*

However, the maximum fault current supplied by the synchronous DER in SWB6 and seen by CB3.1 I_{kmax}=2.4 kA. This will activate the L part of the relay's trip curve with the expected tripping time delay of 25 s. During this time DER in SWB6 will be disconnected by its out-of-step protection.

In order to guarantee fast fault isolation in the islanded mode where the main grid does not contribute to the fault, the trip curve must be pushed to the left dynamically depending on the microgrid topology and a number of connected DERs (1). DERs that have to be taken into consideration are the subset of units that contribute to the short circuit current on the defined direction.

$$I_{k\min} = \sum_{1}^{n} k_{DER} * I_{rDER} \tag{1}$$

where I_{rDER} is a rated output current of a particular DER and k is a fault current contribution coefficient (2).

$$k = \frac{I_{kDER}}{I_{rDER}} \tag{2}$$

where I_{kDER} is a fault current supplied by a particular DER. This coefficient is set at 1.1 for DERs with power electronics interfaces and at 5 for synchronous DER units. The modified trip curves for scenario B2 are illustrated in Figure 19. Protection settings for all CBs in the island are calculated during the off-line fault analysis and shown in

Table **5** as recorded in the event and action tables. Another protection alternative is based on the adaptive directional interlock (Section 3.3). The tripping time is set at 100 ms for all CBs inside the island and the minimum short circuit current has to be dynamically modified (reduced).

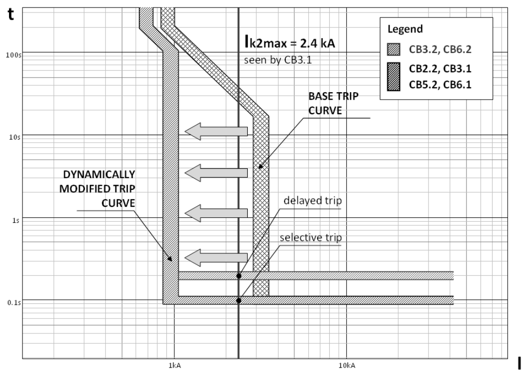

Figure 19: *Base case and modified trip curves and a tripping sequence in Scenario B2 (Figure 18).*

Table 5: Scenario B2: Modified OC Protection Settings I_{KMIN} and t_S

Upper feeder		CB1	CB2	CB1.1	CB1.2	CB2.1	CB2.2	CB3.1	CB3.2
		1	1	1	0	0	1	1	1
	I_{kmin}	3.2	3,2	3.2	3.2	3.2	1.2	**1.2**	**1.2**
	t_s	0.5	0.4	0.4	0.3	0.3	0.1	**0.1**	**0.2**
Lower feeder			CB3	CB4.1	CB4.2	CB5.1	CB5.2	CB6.1	CB6.2
			1	1	0	0	1	1	0
	I_{kmin}		3.2	3.2	3.2	3.2	1.2	1.2	**1.2**
	t_s		0.4	0.4	0.3	0.3	0.1	0.1	**0.2**
DER + load	CB1.3	CB1.4	CB1.5	CB2.3	CB2.4	CB2.5	CB3.3	CB3.4	CB3.5
	1	1	1	0	1	1	0	1	1
DER + load	CB4.3	CB4.4	CB4.5	CB5.3	CB5.4	CB5.5	CB6.3	CB6.4	CB6.5
	0	1	1	0	1	1	1	1	1

5 CONCLUSIONS

In this paper, the effect of DERs and topological changes on sensitivity and selectivity of microgrid protection (loss of relay coordination) is investigated. A novel adaptive microgrid protection system using digital relaying and advanced communication infrastructure is proposed.

The adaptive protection system is based on a centralized architecture with pre-calculated information where protection settings are updated periodically by the microgrid central controller with regard to a microgrid operating state. Settings for non-directional or directional over-current relays are pre-calculated during off-line fault analysis of a given microgrid.

Fault detection and selective isolation are very challenging tasks in microgrids dominated by DER with power electronics interfaces. The proposed solution is based on extension of the microgrids adaptive protection system with a directional interlock.

Several scenarios have been set up to illustrate the effects of adaptation of relay settings. The results of these simulations have been reported and analyzed.

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7 ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of European Commission in co-funding this work through the "MORE MICROGRIDS" Consortium (contract: SES6-019864) and all their partners for their invaluable inputs.

8 APPENDIX

Parameters of utility grid	Value
Rated voltage, V	6000
Short circuit power, MVA	500

Parameters of distribution transformer	Value
Rated voltage primary/secondary, V	6000/400
Rated power, kVA	630
Vcc, %	4
LV distribution system	TN-S

Parameters of cables	Value
Type	EPR/XLPE
Cross-section phase, mm^2	3x185
Cross-section neutral, mm^2	95
Nominal current, A	750
Resistance at 20^0C phase/neutral, mOhm	8.34/16.24
Inductance at 20^0C phase/neutral, mOhm	6.17/6.25
Length, meters	150

Parameters of feeder circuit breakers	Value
Rated voltage, V	400
Rated current, A	800

Parameters of loads	Value
Rated voltage, V	400
Rated current, A	100
Rated power factor, $\cos\varphi$	0.9

Parameters of synchronous DERs	Value
Rated voltage, V	400
Rated apparent power, kVA	160
Rated power factor, cosφ	0.8
Direct-axis sub-transient reactance Xd'', %	9.6
Quadrature-axis sub-transient reactance Xq'', %	10.2
Direct-axis transient reactance Xd', %	21
Direct-axis synchronous reactance Xd, %	260
Negative sequence reactance X2, %	9.8
Zero sequence reactance X0, %	2.1
Direct-axis sub-transient short circuit time constant Td'', ms	11
Direct-axis transient short circuit time constant Td', ms	85