A digital protection procedure for smart grid reconfiguration after faults

F. Muzi, Z. Bayasgalan

Abstract**—**Smart grids can be considered as active, meshed networks. In order to increase the continuity level of power supply in these systems, it is of fundamental importance to quickly detect the presence and location of a fault and afterwards to reconfigure the network automatically, eliminating the faulted line-segment as fast as possible. Therefore, it is particularly important to draw up a selectivity plan which could prove accurate and valid for most possible faults. From this point of view indeed, the use of a proper selectivity coordination and the adoption of new-generation digital relays may substantially increase the supply continuity level of smart grids, which are being more and more widely implemented. The paper presents a fast, robust method based on a particular logic selectivity procedure that can be advantageously used also in the presence of Distributed Generation (DG). Moreover, the operation zones and setting of the proposed digital protection system are presented and explained. Finally, some problems of protection systems in the presence of DG are also discussed and commented.

Keywords**—**Digital relays, Power system protection, Protective coordination, Selectivity, Smart grids.

I. Introduction

TIPICALLY a smart grid can perform real-time collection and processing of a large number of information from the field, using the approaches typical of Information and Communication Technology (ICT) [1]-[3]. Its main features include the use of electronic devices and controls, the integration of distributed energy resources, growing energy market liberalization [4]-[8], the adoption of self-healing and "peak-shaving", energy storage techniques and more [9].

In other words, a smart grid represents an interesting confluence of different skills from Power Systems, Power Electronics, Instrumentation, Protection, Control, Monitoring and ICT.

In this context, it is quite clear that flexible, safe, fast and reliable protection systems are among the most critical issues for a correct operation of a smart grid.

In practice, both power system Protection and Control and Monitoring (PCM) are treated by smart grid operators as one complex matter to be faced as a whole. As a matter of fact, in future years digital protection will be using more powerful, probably even cheaper microprocessors, and new digital processing concepts will be adopted, as indicated in IEC 61850.

Moreover, as concerns hardware sensors, a complete platform was developed to interface simultaneously with a number of protection, metering and control devices installed in an automated substation [10].

The complexity of smart grids also requires timely, fast and selective protection systems, in order to improve reliability, quality and efficiency so as to reach the new targets required in the forthcoming era of electric energy distribution and management.

In this context, the development of smart grids requires also new, intelligent wide-area protection systems able to quickly process information from the field, first in order to assure the power network security and then to rearrange the system in a new configuration so as to reduce, as much as possible, the extension of the faulted area that is to be isolated from the remaining healthy system.

II. Problem Formulation

First of all, the electric Medium Voltage (MV) distribution system shown in Fig. 1 is assumed as a reference. At the top there are the primary HV/MV substations while at the bottom there are both secondary MV/LV substations and different MV line-segments, that is to say the MV distribution system examined in this paper.

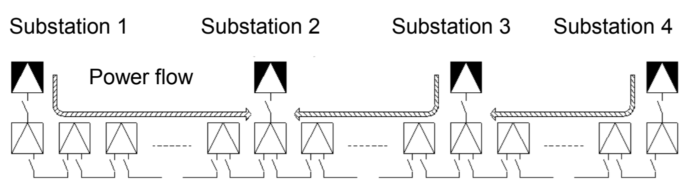

Fig. 1. The scheme of the MV reference system.

The system can be considered as a distribution network with meshed configuration, since different supply sources are present, but at the same time its arrangement can be changed by automatically opening or closing disconnectors at the two ends of each line segment.

Fig. 2 shows the coverage of the instantaneous relays. The

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first attempt to define a selectivity plan is usually based on the use of amperometric selectivity. In this case, the instantaneous release of the protection installed at the *a* point (Fig. 2), in order not to interfere with one of the protections installed at the *b* point, must be calibrated for a current at least 25% higher than the value of the maximum short-circuit current set at the release placed at the beginning of the next line-segment.

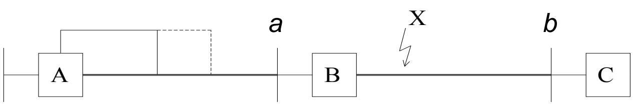

Fig. 2. Coverage of the instantaneous relays (points *a* and *b*).

These margins usually imply that an instantaneous protection covers only 40-70% of the line.

Fig 3 shows details of two consecutive MV/LV substations from the diagram in Fig.1.

In the following, short circuit currents are computed for a case study performed to accurately verify the possibility of adopting amperometric selectivity [11].

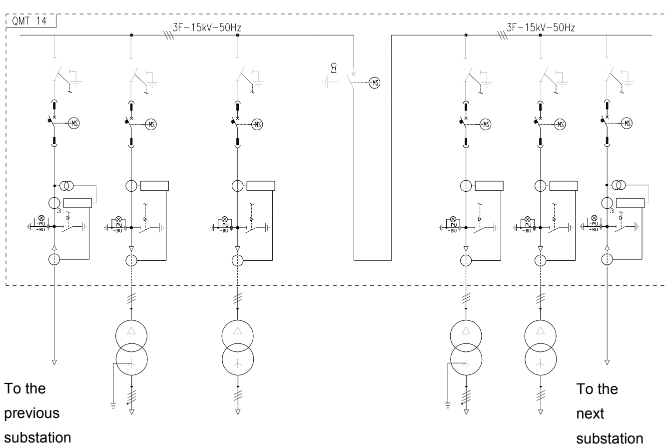

Fig. 3. Details of two secondary, consecutive MV/LV substations from the diagram in Fig.1.

The I_{SC} short-circuit currents were calculated in a simply way with the following relations:

$$Z_{net} = \frac{1.1 \cdot V_n}{\sqrt{3} \cdot I_{sc}} \Rightarrow X_{net} = 0.995 \cdot Z_{net};\ R_{net} = 0.1 \cdot X_{net}$$

$$X_{C-MV} = X_{C-km} \cdot \ell_{MV}, \quad R_{C-MV} = R_{C-km} \cdot \ell_{MV}$$

$$R_{tot} = (R_{net} + R_{C-MV}), \quad X_{tot} = (X_{net} + X_{C-MV})$$

$$Z_{tot} = \sqrt{(R_{tot})^2 + (X_{tot})^2}$$

$$I_{sc} = \frac{1.1 \cdot V_n}{\sqrt{3} \cdot Z_{tot}}$$

The results of the calculations for a real case study, partially represented in Fig. 3, show that differences between currents are too low, more specifically:

$$I_{sc,n} < 1.25 \cdot I_{sc,n+1}$$

This implies that it is not possible to selectively set instantaneous protections if amperometric selectivity is adopted. It is therefore necessary to use another type of selectivity. In the next section, the use of a new logic selectivity able to solve the problem is presented.

III. Proposed Logic Selectivity

The kind of logic selectivity proposed works as follows. A protection placed along the *nth* line-segment detects a fault but does not trip since it keeps waiting for a response from the *n+1* protection for a certain time interval. If the *n+1* protection detects a fault, *n* does not operate because it means that the fault is in the subsequent sections; on the contrary, if the *n+1* protection does not communicate the presence of a fault, the *n* circuit breaker trips at the right time. It is important to point out that the system is intrinsically safe because in case of communication inconveniences the *n* protection will surely trip, even if in an untimely manner. As a back-up protection, the *nth* circuit breaker trips although the subsequent relay communicates the presence of a fault, of course with a further delay.

In addition to a fault along a line, also a fault on the MV bus-bars can occur; however, the clearing of this fault is obvious. As concerns total intervention time, let us assume the network scheme of Fig. 4 and a digital protection communicating through a Modbus network on the basis of the logic program illustrated in Fig. 5.

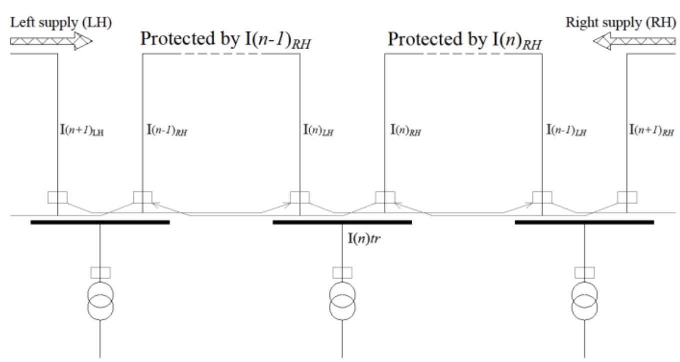

Fig. 4. System layout with the protection mechanism.

Then, Fig. 6 shows all the time intervals necessary for the intervention, which amount to about 100 ms altogether.

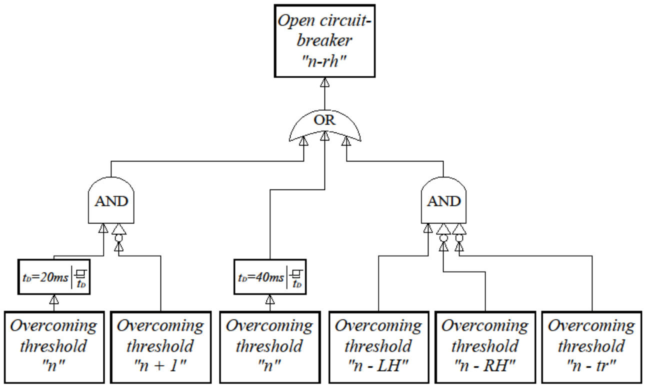

Fig. 5. Logic diagram of the *nth* digital protection.

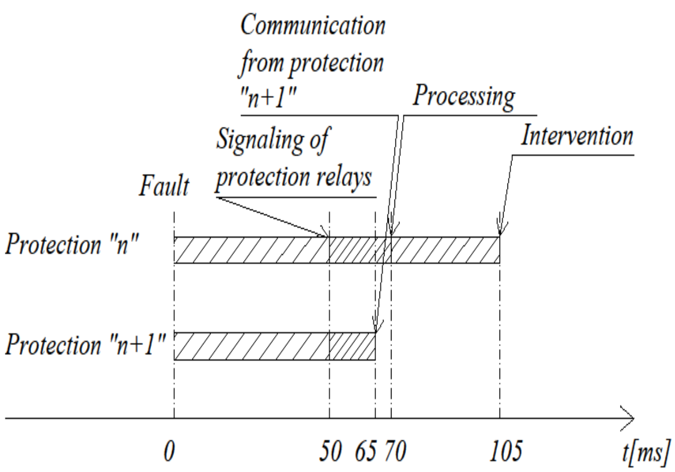

Fig. 6. Intervention times for the proposed logic.

In short, a partial conclusion is that logic selectivity allows to correctly protect the system from phase faults. With regard to earth faults, as shown in Fig 7, if a fault affects the user's installation, the current detected by the protection mainly consists of the resistive component, since capacitive currents are compensated by the Petersen coil. In the case of an isolated neutral, the capacitive component is in advance with respect to voltage.

As concerns MV/LV private substations, if the fault occurs on the side of the utility company, in the event of a compensated neutral a capacitive current generated by the user's lines will flow, whereas in the case of an isolated neutral the current will be delayed in comparison to voltage. Directional protections are calibrated so as to have a non-operation and an operation zone [12], [13]. Angles, as established by the utility company, are shown in Fig. 8.

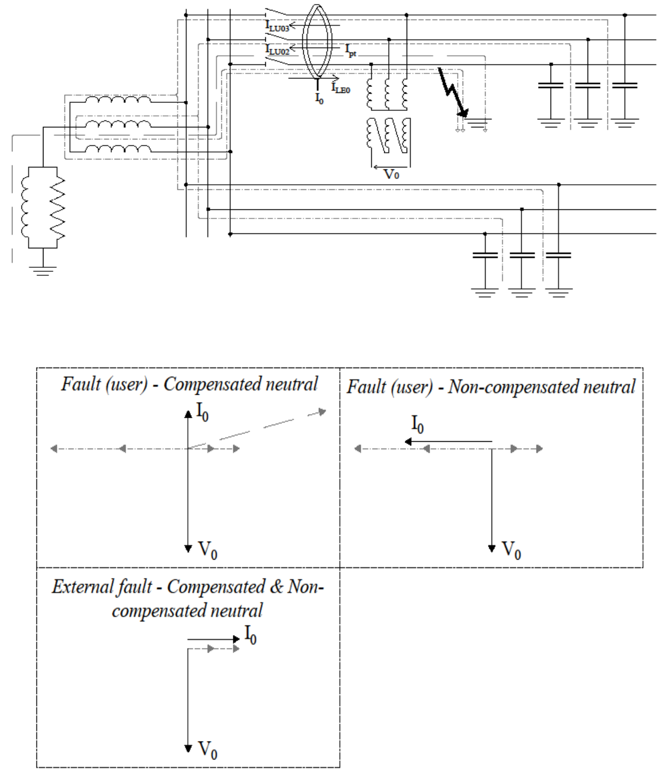

Fig. 7. Conditions for a ground fault, electrical scheme and phasor representation.

In case of a double ground fault, the current is much higher and is detected by the relay with the zero-sequence current threshold set at 150 A.

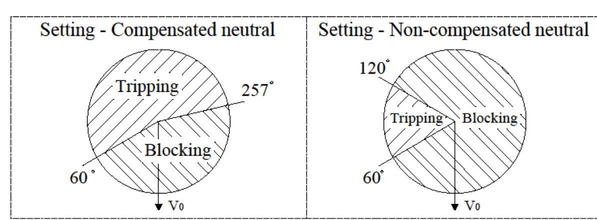

Fig. 8. Calibration of a directional protection.

In the case of a ground fault, tripping times are broader; for example, in the case of a compensated neutral intervention time is 0.6 s.

Selectivity is still of a logic type, since protections are already communicating with each other for phase faults, and therefore no additional costs are involved. The logical criteria are the same as explained previously.

IV. THE NETWORK RECONFIGURATION ALGORITHM

The automation system has the task of carrying out a reconfiguration of the network in case of faults [14]-[23]. The implemented reconfiguration program is illustrated with reference to the network layout in Fig 9 (double-fed system). The network consists of four line-segments and is fed at both ends.

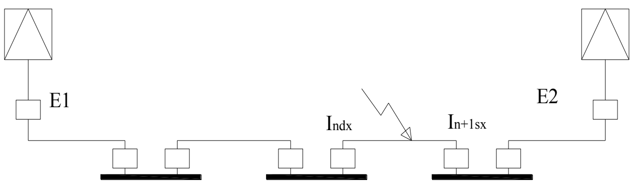

Fig. 9. The system configuration of a case study performed.

Let us suppose a fault occurs within the no. 3 line-segment. With reference to Fig. 9, the protection system identifies the faulted line-segment and opens the I_{nRH} circuit breaker.

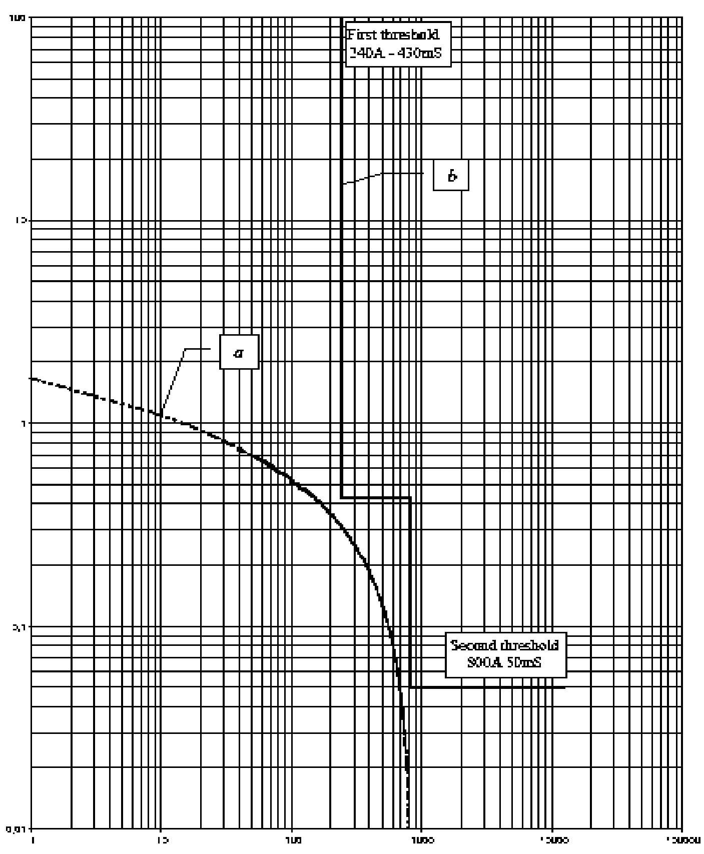

Fig. 10. Comparison of the characteristics of the transformer inrush current (a) and the circuit-breaker intervention (b).

As a first action, the reconfiguration system will open the I_{n+1LH} circuit breaker to isolate the faulted line-segment. At this point only the *E2* circuit-breaker needs to be closed to feed the entire system. Here two main problems arise: first, the need to verify power availability at the *E2* feed, and secondly the magnetization current of the transformers that may be connected with the closing of the *E2* circuit breaker.

The former problem is solved by storing the previously performed network operations in a memory, knowing at the same time the maximum power available from the utility company. The latter problem is solved by dividing the line into steps so as to ensure that the transformer inrush currents are lower than the calibration of the general device installed at the substation.

The creation of these steps is ensured by the presence of undervoltage protections installed at certain special devices.

As an example, Fig. 10 shows the inrush current of a 3250kVA power transformer compared with the time-current characteristics of the MV installed circuit breaker. Fig. 10 shows a correct coordination between the two curves.

V. COMMUNICATION PROTOCOLS

As a rule, communications between different sensitive devices installed inside substation take place according to a MODBUS protocol, placed at level 7 of the OSI (application Layer). The different implementation types of a Modbus protocol are shown in the following:

- TCP/IP –ETHERNET;

- Serial asynchronous transmission applied with various supports (EIA/TIA 232 E, EIA/TIA 422, EIA/TIA 485 A, optical fiber, radio, etc.);

- MODBUS PLUS with a fast dedicated channel.

As concerns the OSI Application Layers, Fig. 11 and table 1 show the Modbus communication stack and layer levels, respectively.

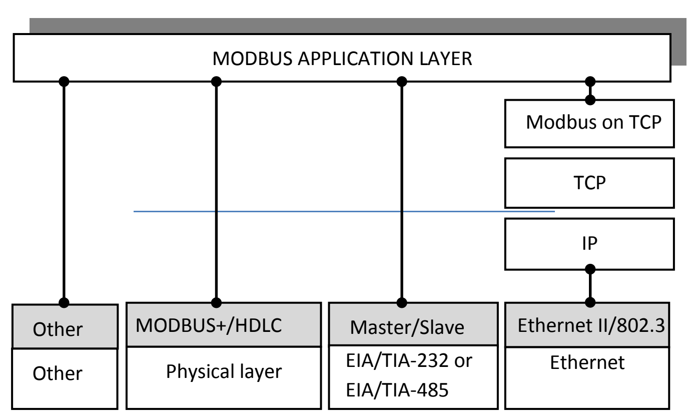

Fig. 11. Modbus communication stack.

TABLE I
COMPARISON BETWEEN OSI AND MODBUS LEVELS

Layer	ISO/OSI MODEL	MODBUS MODEL
7	Application	Modbus Application Protocol
6	Presentation	Empty
5	Session	Empty
4	Transport	Empty
3	Network	Empty
2	Data link	Modbus Serial line Protocol
1	Physical	Modbus Master/Slave, Ethernet, etc.

VI. SOME REMARKS

An important, as yet unsolved problem with smart grids involves the present criticality of network infrastructures for renewables and distributed generation. Actually, the intermittency of large scale renewable energies in combination with a necessarily distributed-type generation introduces a further challenge, namely the management of power flowing back and forth along the grid. Any possible solutions to this problem may further increase the importance of automation and control systems.

On the other hand, the acquisition and quick processing of data coming from different system points has become a necessary condition to undertake actions which have to be fast, timely and selective. The availability of digital data actually allows both the effectiveness of automation systems and suitable real-time diagnostics, improving the reliability and efficiency of the electrical system [24].

As far as emergency management in electrical power systems is concerned, the nowadays widely used, fast digital relays, if properly modified, can provide a fundamental contribution also in grids that have become active thanks to DG [25]-[27]. These protections are not, as a rule, designed to talk to each other during fault or anomalous conditions; on the other hand, information exchange through a robust communication network is of paramount importance to establish the best course of action in any event, since the hierarchies of actions to be performed can be redefined (via software) in real time according to the occurrence and evolution of events. In order to achieve this aim, new algorithms are to be implemented and distributed intelligence devices, possibly coordinated by a supervisor, are to be used.

Moreover, with reference to DG, it may be useful to mention another problem. It is well known that the massive penetration of DG has led to a new concept of distribution networks, characterized at certain day times by reverse power flow, precisely due to the presence of "active users".

The problem is particularly worrying if at the sending sections of the MV lines there are only simple overcurrent protections, normally unable to distinguish current direction. In this scenario, a particularly alarming condition is represented in Fig. 12, where untimely tripping can happen at the healthy *B* line when the fault is in the *A* line.

The directional, digital protections proposed in this paper can effectively solve also the above-mentioned problem.

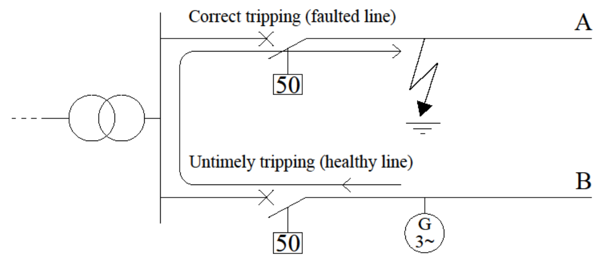

Fig. 12. Example of untimely tripping in a primary substation due to the massive presence of DG along the lines.

VII. POSSIBLE FUTURE DEVELOPMENTS

In electric energy distribution the time has finally come for radical changes in efficiency, reliability and security, and industry is now ready to invest in developing the advanced technologies [28], [29] necessary to improve the new smart grids. As a matter of fact, these must be managed and controlled by a set of advanced, digitally-based technologies, which include phasor measurement, centralized and integrated voltage and VAR controls, grid automation, advanced monitoring and diagnostics. The expected improvements will affect network power quality and security, and be verified by means of remote, real-time inspection performed through new telecommunication systems using advanced encryption [24].

In combination with the new challenges coming from the need to safeguard the environment while at same time assuring the required energy, a great many new technologies will soon reshape the traditional fundamentals of electrical distribution, including power protection systems. Some of the technologies required to implement smart grids are already available on the market. Basic SCADA (Supervisory Control And Data Acquisition) systems have actually evolved towards DMS (Distribution Management System), and Geospatial information systems (GISs) can be integrated with Outage Management Systems (OMSs). New advanced sensors allow accurate, real-time evaluations of network performances. Advanced Metering Infrastructures (AMIs) in combination with Fault Detection, Isolation and Recovery (FDIR) systems are a powerful means to reduce both the SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index).

On the other hand, differently from the estimated, approximated methods used in the past, the present accuracy of outage reports may increase the CAIDI (Customer Average Interruption Duration Index), while quick automatic service restorations may cause a shift of events from SAIFI into MAIFI (Momentary Average Interruption Frequency Index). This may lead to further investments in research targeted at improving grid power quality and reliability.

VIII. CONCLUSION

As far as emergency management is concerned in electrical power systems, the nowadays widely used, digital fast relays, if properly modified, can provide a fundamental contribution also in grids that have become active thanks to DG. These protections are not, as a rule, designed to talk to each other during fault or anomalous conditions; on the other hand, information exchange through a robust communication network is of paramount importance to establish the best course of action in any event, since the hierarchies of actions to be performed can be redefined (via software) in real time according to the occurrence and evolution of events. In order to achieve this aim, new algorithms are to be implemented and distributed intelligence devices, possibly coordinated by a supervisor, will have to be used. In the paper a method is illustrated, based on logic selectivity and the use of new generation digital protection, which appears to be particularly effective, fast and robust. Moreover, a network automatic reconfiguration are presented as additional procedures that can substantially improve a system's reliability and supply continuity.

REFERENCES

[1] M. Y. Vaziri, S. Vadhva, S. Ghadiri, C. J. Hoffman, and K. K. Yagnik, "Standards rules, and issues for integration of renewable resources," Power and Energy Society General Meeting, 2010 IEEE, pp.1-8, 25-29 July 2010.

[2] *Europe Commission*, EU SET–Plan Strategic Energy Technology Plan, 2011, http://ec.europa.eu/energy/technology/set_plan/set_plan_en.ht

[3] *Europe Commission*, European Smart Grid, 2011, Available: http://www.smartgrids.eu/

[4] Zagdkhorol, B., Tsetsgee, B., "Score for the model of Mongolian competitive electricity market and the possibility of improving its functioning, strategic technology," *in Proc. (IFOST), 2010 International Forum , Ulsan, Korea*, pp. 216–219.

[5] Zagdkhorol, B., "Market mechanism of Mongolian competitive electrical market," *in Proc. International Scientific and Technical Conference -"Science and Education 2011",* Murmansk State. Reg. STC "Informregistr" № 0321100504, 4 - 8 April 2009.

[6] Zagdkhorol, B., Tsetsgee, B., "Modeling of balancing market for competitive wholesale electricity market," *in Proc. Strategic Technology (IFOST), 2011 6th International Forum*, vol.1, no., pp.609-613, 22-24 Aug. 2011.

[7] Zagdkhorol, B., B. Tsetsgee, "Mathematical models of the electricity market," in Proc. *Applied Mathematics in science, "Science and Technology Conference*, Mongolia, Ulaanbaatar, 2012.

[8] Zagdkhorol, B., Tsetsgee Bayasgalan, "Real-time balancing services in the electricity market," *in Proc. Strategic Technology (IFOST), 2012 7th International Forum*, vol., no., pp.1,4, 18-21 Sept. 2012.

[9] C. Heng, W. Yanping. *Technical Discussion of Relay Protection in Smart Grid*, Science & Technology Information, 2010.

[10] D. Chatrefou, J. P. Dupraz, G. F. Montillet, "Interoperability between non-conventional instrument transformers (NCIT) and intelligent electronic devices (IED)," *in Proc.* 2005/2006 *IEEE Power Engineering Society (PES) Transmission and Distribution Conf. and Exhibition*, *pp. 1274-1279, May 2006.*

[11] F. Muzi, "Logic selectivity for an automatic reclosing and reconfiguration of electrical distribution systems," *in Proc*. *WSEAS International Conference on Information Technology and Computer Networks (ITCN '12)*, Vienna, Austria, November 10-12, 2012.

[12] M. Gong, X. Zhang, Z. Gong, W. Xia; J. Wu, C. Lv, "Study on a new method to identify inrush current of transformer based on wavelet neural network," *in Proc. Electrical and Control Engineering (ICECE*), 2011

[13] M.G. Kanabar, I. Voloh, D. McGinn, "Reviewing smart grid standards for protection, control, and monitoring applications," *in Proc. Innovative Smart Grid Technologies (ISGT), 2012* IEEE PES, 2012.

[14] G. Fazio, V. Lauropoli, F. Muzi, and G. Sacerdoti, "Variable-window algorithm for ultra-high-speed distance protection," *IEEE Trans. on Power Delivery* - Vol. 18, N. 2, April 2003.

[15] C. Bartoletti, G. Fazio, F. Muzi, S. Ricci, and G. Sacerdoti, "Diagnostics of electric power components: an improvement on signal discrimination," *WSEAS Trans. on circuits and systems*, Issue7, Vol. 4, July 2005.

[16] F. Muzi, C. Buccione, and S. Mautone, "A new architecture for systems supplying essential loads in the Italian High-Speed Railway (HSR)," *WSEAS Trans. on Circuits and Systems*, Issue 8, Volume 5, August 2006

[17] F. Muzi, and L. Passacantando, "Improvements in power quality and efficiency with a new AC/DC high current converter," *WSEAS Trans. on Circuits and Systems*, Issue 5, Volume 7, May 2008.

[18] F. Muzi, "Real-time voltage control to improve automation and quality in power distribution," WSEAS Trans. on Circuits and Systems, Issue 4, Volume 7, April 2008

[19] F. Muzi, M. Barbati, "A real-time harmonic monitoring aimed at improving smart grid power quality," *in Proc. 2011 IEEE International Conference on Smart Measurements for Future Grids (SMFG)*, Bologna, Italy, Nov. 14-16, 2011.

[20] Y. Lv, D.You, K. Wang, L. Wang, Z. Chen, and S. Huo, "Study on wide-area backup protection system for the smart grid," in *Proc. Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, 2011 4th International Conference on Digital Object Identifier. 2011.

[21] F. Muzi, R. Dercosi Persichini, "An analysis of overvoltages in large MV-Cable installation," in *Proc. 15th IEEE-ICHQP International Conference*, Hong Kong, 17-20 June 2012.

[22] M. G. Kanabar, I. Voloh, D. McGinn, "Reviewing smart grid standards for protection, control, and monitoring applications," in *Proc. Innovative Smart Grid Technologies (ISGT),* 2012 IEEE PES, 2012.

[23] F. Muzi, Z. Bayasgalan, "Selectivity and coordination of protection systems for an effective smart grid reconfiguration," in *Proc. 4th International Conference on Development, Energy, Environment, Economics (DEEE '13),* Paris, France, October 29-31, 2013.

[24] F. Muzi, M. Gimenz De Lorenzo, G. De Gasperis, "Intelligence improvement of a "prosumer" node through the predictive concept", in *Proc. IEEE-EMS 2012, UKSim-AMSS 6th European Modelling Symposium on Mathematical Modelling and Computer Simulation*, Malta, 14–16 November 2012.

[25] F. Muzi, A. De Sanctis, P. Palumbo, "Distance protection for smart grids with massive generation from renewable sources," in *Proc. The 6th IASME/WSEAS International Conference on Energy & Environment (EE'11)*, Cambridge (UK), 2011.

[26] F. Muzi, "Real-time voltage control to improve automation and quality in power distribution," *WSEAS Trans. on Circuits and Systems*, Issue 4, Volume 7, April 2008.

[27] M. Cerullo, G. Fazio, M. Fabbri, F. Muzi, and G. Sacerdoti, "Acoustic signal processing to diagnose transiting electric-trains." *IEEE Trans. on Intelligent Transportation Systems*, Vol. 6, No. 2 June 2005.

[28] R. Zagdkhorol, B., "Unit commitments technology," in *Proc. VII International Conference "Improving the efficiency of electricity" PEPE 2009*. Novocherkask, Russia, 2009.

[29] Zagdkhorol, B., Tsetsgee B., "Mathematical model for Unit Commitment Technology in Mongolian Competitive Electricity Market," in *Proc. The international conference on optimization. Simulation and control 2010, (ICOSC-2010)*, Ulaanbaatar, Mongolia, July. 25-28, 2010.

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