U.P.B. Sci. Bull., Series C, Vol. 74, Iss. 1, 2012 ISSN 1454-234x

AUTOMATIC LOAD RECONNECTION AFTER EMERGENCY UNDERVOLTAGE LOAD SHEDDING

Bogdan OTOMEGA[1], Lucian TOMA[2], Constantin BULAC[3], Thierry VAN CUTSEM[4]

The load shedding amount can be easily determined off-line, for predefined contingencies and system status, but the computation methods can hardly be embedded in a real-time system protection scheme facing an unknown disturbance. Instead, the load shedding scheme proposed by the authors was provided with a possibly sub-optimal but simple and robust logic which allows choosing the location, the amount of load to shed and the delay before shedding. Even if it may lead to shedding some more load, these criteria make sense in terms of reducing the nuisance caused to customers by low voltages. In this context, in this paper the authors report the results obtained with an automatic load reconnection controller which attempts to reconnect a portion of load after an emergency load shedding action. Detailed time simulations of a test system are reported.

Keywords: long-term voltage instability, emergency load shedding, load reconnection

1. Introduction

Load shedding is a cost-effective countermeasure against voltage instability triggered by large disturbances [1-3]. To this purpose some event-based and response-based protection schemes have been successfully developed and tested [4-8]. Among them, the response-based schemes adjust the corrective action to the disturbance severity and location and operate in closed loop for higher robustness. Such a protection scheme against long-term voltage instability was previously proposed in [9] and extented in [10] in order to also deal with the impact of induction motor loads. In order to cope with the fast response of motor loads, additional information exchange was required in order to enable the protection to act with reduced time delay.

It was previously shown that in the presence of induction motor loads the load shedding controllers should react very fast, therefore important amounts of load might be shed in a very short time interval in order to stop the voltage decay.

[1] Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania
[2] Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania
[3] Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania
[4] Fund for Scientific Research (FNRS) and Department of Electrical Engineeering and Computer Science (Montefiore Institute), University of Liège, Belgium

As already stated in [9] and [10] due to the control scheme of the controllers, which does not involve controller coordination via a communication system, control actions being based only on voltage time evolution, the amount of load shed might be sub-optimal. By doing so, even if the amount of load shed is larger, the nuisance caused to customers due to low voltages is reduced.

Eventhough the optimum amount of load shedding can be computed off-line, for a predefined set of contingencies and a certain system state, this computation can hardly be included in a protection scheme that should act in real-time, facing an unknown disturbance.

Therefore, after the emergency load shedding and system stabilization, one may think that part of the load that was initialy disconnected could be reconnected as long as the system response is acceptable. To this purpose in this paper an automatic load reconnection controller is designed and tested.

This paper is organized as follows. The principle and action of the load shedding scheme is illustrated in Section 2, while the design of the automatic load reconnection controller is presented in Section 3. The test system on which the proposed automatic controller was installed is presented in Section 4. Section 5 reports on various tests performed on a test system and the paper ends up with conclusions and perspectives for future work.

2. The principle of the load shedding scheme

The undervoltage load shedding protection scheme used in this paper was developed by the authors and relies on a set of controllers distributed over the region prone to voltage instability [9]. Each controller monitors the voltage *V* at a transmission bus and acts on a set of loads located at distribution level and having influence on *V*. Each controller operates as follows:

- it acts when its monitored voltage *V* falls below some threshold V^{th};
- it can act repeatedly, until *V* recovers above V^{th}, therefore it acts in closed-loop;
- it waits in between two sheddings, in order to assess the effect of the actions taken both by itself and by the other controllers. The time delay τ depends on the time evolution of *V* following the equation:

$$\int_{t_0}^{t_0+\tau} \left(V^{th} - V(t)\right) dt = C , \tag{1}$$

where *C* is a constant to be adjusted and t_0 is the time instant when the monitored voltage becomes smaller than the voltage threshold. This control law yields an inverse-time characteristic: the deeper the voltage drops the faster the load shedding. Therefore the delay between successive sheddings varies with the severity of the situation;

- the amount shed is also depending on the time evolution of V following the equation:

$$\Delta P^{sh} = K \cdot \frac{1}{\tau} \cdot \int_{t_0}^{t_0+\tau} \left(V^{th} - V\left(t\right)\right) dt\,, \tag{2}$$

where K is also a constant that needs to be adjusted.

The above relationship transposes the voltage drop severity into load shedding amplitude: the larger voltage drop the larger the amount of load shed. It was demonstrated in [9] and [12] that with these features the proposed load shedding scheme could adjust its actions to the disturbance location and severity.

In Fig. 1 is illustrated the load shedding action relative to the test system and a contingency considered later on in this paper, for a proportion of 50% of motor load. As can be seen, after the monitored voltage drop below the threshold value (V_{LT}^{th} = 0.85 p.u.), the controllers start to shed load very fast (as the generator limitation signal is sent the controllers are acting with reduced time delay τ^{red} = 0.3 s [10]). Two controllers are acting, C_{1041} and C_{1044}, shedding a total amount of 267 MW, that is 168 MW and 99 MW, respectively.

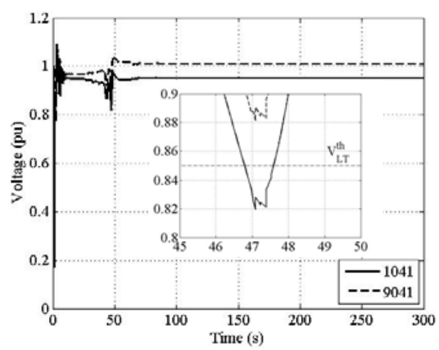


Fig. 1. Evolution of transmission and load voltages for a proportion of 50% with undervoltage load shedding enabled

3. Load reconnection after emergency load shedding

As explained in the previous sections in emergency situations important amounts of load are shed in certain conditions in very short time intervals. If after the load shedding action the system is stabilized and the final profile satisfies basic conditions such as:

- all LTC controlled voltages are in the deadband, with the LTCs not blocked on their limit taps;

- all bus voltages monitored by undervoltage load shedding controllers are above the considered voltage threshold;

load reconnection action could be considered.

To this purpose an automatic load reconnection controller was developed. The controller monitors both the transmission and distribution voltages and acts on a set of loads located at distribution level. The controller needs to monitor the transmission voltage in order not to trigger again the load shedding action by reconnecting load, thus the load reconnection action should be stopped when the transmission voltages are approaching V_{LT}^{th}. Moreover, by reconnecting load, distribution voltages are decreasing too, forcing the LTCs to act in order to keep them in the deadband, therefore controllers should also monitor these voltages as the LTCs might reach their tap limits. In the latter situation, the load reconnection action should be stopped. Such a load reconnection controller was installed in the same locations as the load shedding controllers.

It was considered that once the load reconnection conditions were satisfied fixed blocks of 10 MW are reconnected with a delay of 10 s between two subsequent steps at the locations where the initial load shedding took place.

4. Test system

The proposed control actions were tested on the Nordic32 test system [3]. Its one-line diagram is shown in Fig. 2. The model includes 55 buses, 20 generators, and 22 loads. The long-term dynamics are driven by LTC and OELs acting with various delays. The generators are assumed to be provided with excitation system that takes the least demanding among the AVR and OEL signals. Hence, when load shedding brings relief to the generator, the OEL resets and the AVR regains control with negligible delay. All loads are connected to MV distribution buses controlled by LTCs. The load shedding actions are taking place in the “Central” area where the largest voltage drops are observed. The LTC controlled loads considered for tests are presented in Table I.

The tests reported in this paper considered a proportion of 50 % of motor load. A shunt capacitor is assumed to be connected in parallel with each motor, to meet the specified power factor. This capacitor adds to the one present at the MV bus.

The results provided in this paper relate to a set of disturbances involving the tie-lines between the “North” and “Central” areas as well as the lines connected to bus 4044, one of the buses feeding the area where voltages are the most affected. In all cases, the disturbance consists of a short-circuit applied on the line, very close to one of the end buses, at time instant t = 1 s and cleared after 0.1 s by opening the line at both ends.

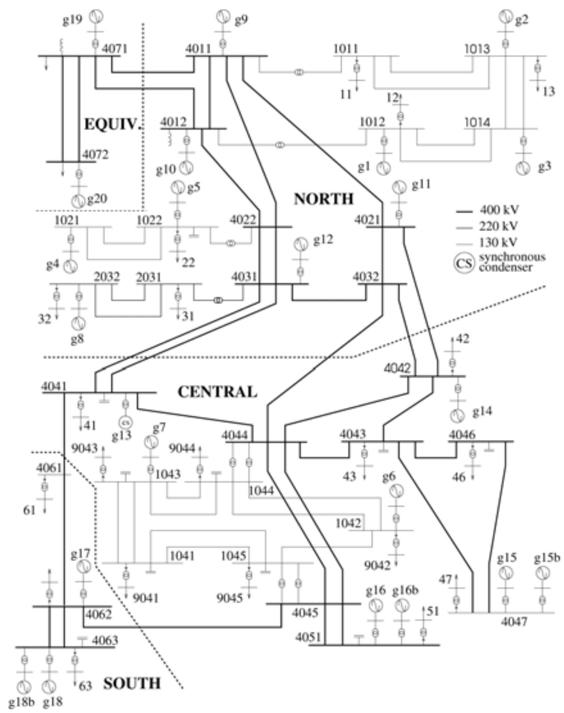


Fig. 2. Nordic32 test system

Table 1

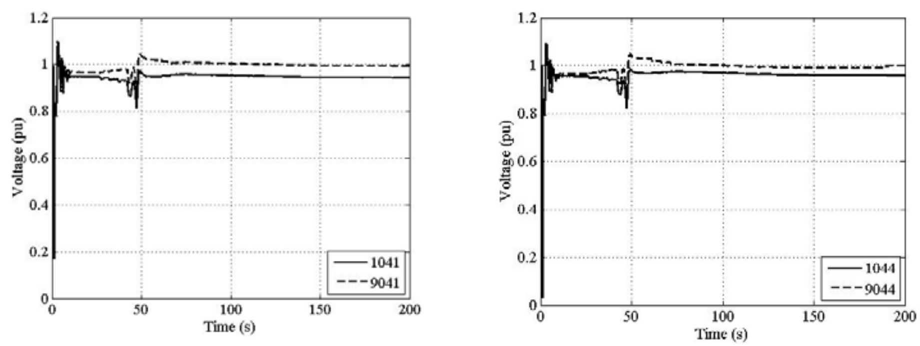
Considered controllers and loads

Controller name	Transmission bus	Load bus	Load [MW]
C_{1041}	1041	9041	600
C_{1042}	1042	9042	300
C_{1043}	1043	9043	230
C_{1044}	1044	9044	800
C_{1045}	1045	9045	700

5. Results

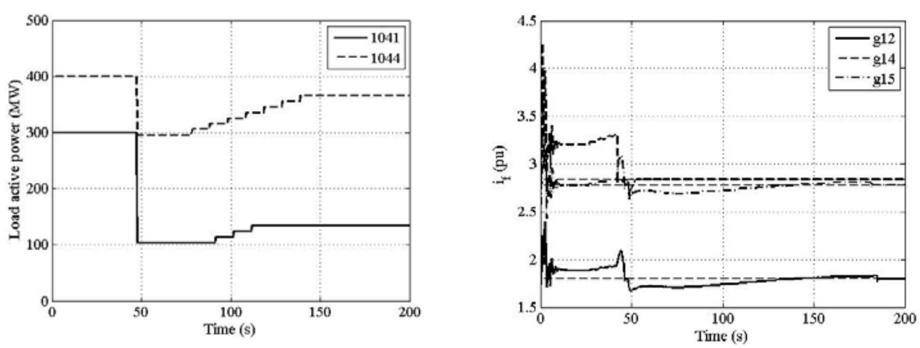
The preliminary tests considered that the load reconnection action is enabled as long as the transmission voltage is above 0.95 p.u. and the distribution voltage is in the LTC deadband. The results are presented in Fig. 3 where the transmission voltages monitored by the undervoltage load shedding controllers that shed load as well as the voltages on the distribution side are illustrated. As can be seen in Fig. 4.*a* where the load evolution is presented, after the load shedding action, as the reconnection conditions are satisfied, the proposed automactic load reconnection controllers succeed to reconnect 100 MW out of the 276 MW initialy shed before the transmission voltages reached the minimum imposed value.

One may think that by decreasing the imposed value on the transmission voltage more load could be reconnected. Preliminary results using a voltage limit of 0.93 p.u., illustrated in Fig. 5, showed that more load can be reconnected (130 MW) but it triggers a second round of load shedding. This is explained by the fact that after the initial load shedding generators g12 and g15 are no longer exceeding their field current limits. Thus, the transmission voltage (the heavy line in Fig. 5.*a*) recovers above the imposed value and the distribution voltage (the dashed line) is brought within limits by the LTC action. Under the effect of load reconnection the two generators exceed their field current limits and get limited leading to transmission voltage decay initiating the second load shedding action. In this scenario the final load shed amount is 510 MW.



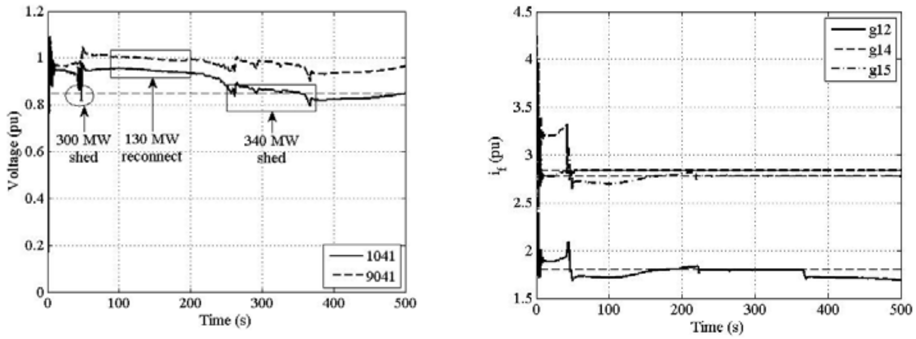
a. *b.*

Fig. 3. Evolution of transmission and load voltages for a proportion of 50% with undervoltage load shedding and automatic load reconnection



a. *b.*

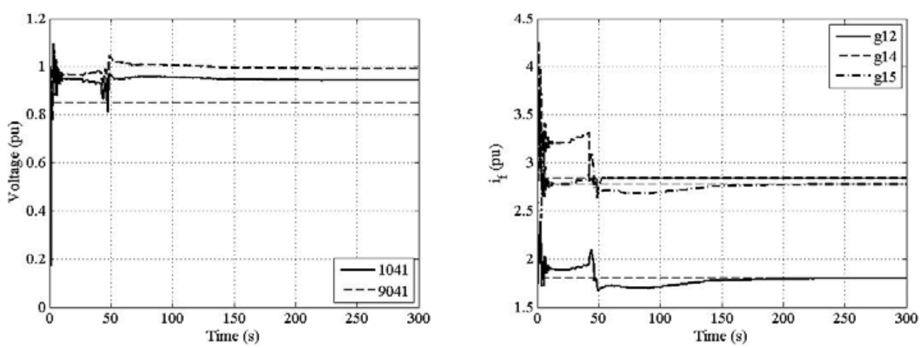
Fig. 4. Evolution of the load in the controlled buses and generators field current for a proportion of 50% with undervoltage load shedding and automatic load reconnection



a. *b.*

Fig. 5. Evolution of transmission and load voltages and generators field current for a proportion of 50% with undervoltage load shedding and automatic load reconnection

In order to avoid the reactivation of the load shedding action the signal from the generators field current used to enable the load shedding with reduced delay was reused in order to stop the load reconnection action once the field current of non-limited generators are approaching limits. In this case the load reconnection action succeeds to supply another 100 MW before being limited by the generators field currents approaching limits (see Fig. 26).



a. *b.*

Fig. 6. Evolution of transmission and load voltages and generators field current for a proportion of 50% with undervoltage load shedding and limited automatic load reconnection

6. Conclusions

With the automatic load reconnection action it was demonstrated once more that the emergency load shedding action is sub-optimal. A substantial part of the load shed could be reconnected without significantly affecting the system state. Furthermore, in the situation that generators located close to the load area are approching their field current limits a signal is required in order to stop the load reconnection in order to prevent them from getting limited. Nevertheless, the amout of load reconnected is still important with respect to the initial amount of load shed.

Further tests, should consider also a decrease in the set-point of the LTCs, which could lead to an initial lower load shedding action and allow an increase in load that can be reconnected.

Acknowledgements

The work has been co-funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement POSDRU/89/1.5/S/62557.

R E F E R E N C E S

[1]. *C. W. Taylor*, "Concepts of undervoltage load shedding for voltage stability", IEEE Trans. on Power Delivery, Vol. 7, 1992, pp. 480-488.
[2]. *S. Arnborg, G. Andersson, D.J. Hill, I.A. Hiskens*, "On undervoltage load shedding in power system", Int. Journal of Electrical Power and Energy Systems, vol. 19, 1997, pp. 141-149.
[3]. *D. H. Karlsson* (convener), System Protection Schemes in Power Networks, Final report of CIGRE Task Force 38.02.19, June 2001.
[4]. *V. C. Nikolaidis, C. D. Vournas*, "Design Strategies for Load-Shedding Schemes against Voltage Collapse in the Hellenic System", IEEE Trans. Power Syst., Vol. 23, No. 2, May 2008.
[5]. *B. Ingelsson, P. Lindstrom, D. Karlsson, G. Runvik, J. Sjodin*, "Special Protection Scheme against Voltage Collapse in the South Part of the Swedish Grid", Proc. CIGRE Conference, 1996, Paper No 38-103
[6]. *D. Lefebvre, C. Moors, T. Van Cutsem*, "Design of an undervoltage load shedding scheme for the Hydro-Quebec system", Proc. IEEE PES General Meeting, Toronto (Canada), July 2003.
[7]. *S. Imai*, "Undervoltage load shedding improving security as reasonable measure for extreme contingencies", Proc. IEEE PES General Meeting, San Francisco (USA), 2005.
[8]. *F. Capitanescu, B. Otomega, H. Lefebvre, V. Sermanson, T. Van Cutsem*, "Prospects of an improved system protection scheme against voltage instability in the RTE system", Proc. 16th Power System Computation Conference (PSCC), Glasgow (UK), June 2008.
[9]. *B. Otomega, T. Van Cutsem*, "Undervoltage load shedding using distributed controllers," IEEE Trans. Power Syst., vol. 22, no. 4, pp. 1898-1907, Nov. 2007.
[10]. *B. Otomega, T. Van Cutsem*, "Local vs. wide-area undervoltage load shedding in the presence of induction motor loads", 2009 IEEE PowerTech Conference, June 28 - July 2, Bucharest, Romania.
[11]. *B. Otomega, T. Van Cutsem*, "A load shedding scheme against both short- and long-term voltage instabilities in the presence of induction motors", 2011 IEEE PowerTech Conference, June 28 - July 2, Trondheim, Norway.