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Techno-Economic Impacts of Automatic Undervoltage Load Shedding Under Emergency

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Abstract — Different schemes for voltage control under emergency are adopted in different jurisdictions around the world. While some features, such as Automatic Voltage Regulation (AVR), are common in all countries, for what concerns undervoltage load shedding (UVLS), to contrast voltage instability or collapse, different schemes are adopted. Most US transmission system operators (TSOs) adopt automatic UVLS schemes, with different capabilities and settings while TSOs in EU usually do not implement automatic UVLS but leave the decisions to the control room operators. The two options may lead to different impacts in terms of trajectory and final status of the transmission grid under emergency, with different unserved energy. In this paper we analyze the impacts from a technical and economic perspective, modeling the grid behavior with different UVLS schemes (none, manual and automatic). The comparison between the different schemes is done resorting to the Incident Response System (IRS), a software tool developed by the authors in the EU-FP7 SESAME project. An illustrative example to a realistic test case is presented and discussed. This paper shows that automatic UVLS is superior to Manual UVLS, from both technical and economic point of view, due to the fast evolution of voltage collapse phenomena and insufficient time for system operators' manual reaction. The benefits of the scheme involving the automatic UVLS can be then compared with the investment costs of equipping the network with those devices.

Keywords— UnderVoltage Load Shedding, voltage collapse, power system security, voltage protection, blackout.

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1. INTRODUCTION

From historic blackouts [1], [2], [3], one can observe that the main factor of most of recent system disturbances is voltage collapse, rather than the underfrequency conditions, which were prevalent in the blackouts of the 1960 and '70s. In some power grids, such as the ones in North America, most of generation sources are located remotely from load centers and there is reluctance to allow building new generation plants in urban areas. This increases the power system dependency on the transmission network and, in case of transmission lines trip, there may be a lack of reactive power in local areas. Therefore, in these transmission systems, the protection against voltage collapse is crucial.

In the operation of power systems, when several failures happen simultaneously, commonly used protection relays (low voltage, over current) may not be able to distinguish between the voltage/current violations caused by widespread cascading failures from those caused by a local fault. This would result in more generators or lines being tripped, spreading the blackout area. So dedicated strategies for undervoltage protection are needed to avoid large scale cascading failures.

An analysis performed on blackouts happened in Europe in the past 35 years [21] clearly shows that most of them were characterized by low voltage or voltage collapse, during the cascading failure, that eventually led to power outage (Table I).

It appears that frequency and gravity of blackout events are increasing in recent years and, due to interdependency of other infrastructures with power system, the blackout impacts on other infrastructures and society are growing. One type of system instability which can occur when the system is heavily loaded is voltage collapse [22]. Other reasons for voltage instability and collapse can be the dynamics of tap-changing transformers [23], as these components can aggravate rapid voltage decay [24], [25], the presence of a high percentage of loads constituted by induction motors [26], and the presence of small noise in load demand [27].

These concerns bring the necessity of reinforcing electrical infrastructures against undervoltage incidents and investing on new protection schemes to prevent huge negative impacts.

Suitable strategies for prevention of voltage collapse are required in order to save costs and mitigate socioeconomic impacts. From the structural point of view, the most effective

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improvement of voltage stability limits is building new transmission lines and increasing generation. But it is very difficult and expensive to find a new corridor for a transmission line or a new location for power plants, since the acceptance of new infrastructures by the population is everyday decreasing. Therefore, new solutions are being investigated to prevent larger blackouts in a more acceptable and economic way. When searching for schemes to enhance power system voltage stability, the evolution of adverse events needs to be analyzed [25].

In today's transmission systems the problem of reactive power reserve is growing because of the restructuring of the power systems involving electricity markets [28]. The voltage and reactive power control are now partially ancillary services that need to be provided by the producers (in contrast with their economic objectives) to system operators [29]. In this framework most of the TSOs are finding it difficult to meet regulatory standards and criteria without using automatic transmission controls such as reactive switching, Remedial Action Scheme (RAS) [30], and Undervoltage Load Shedding (UVLS). Among these control actions, UVLS is becoming more advantageous, being reliable and cost-effective in preventing voltage collapse [31].

UVLS is widely used in the US while in EU the ENTSO-E recommends to implement it within DSOs grids, but up to now it is not widespread [32]. In order to guide system operators to make decisions on when and where to allocate undervoltage protection systems, a cost-benefit based supporting tool is needed. We resort to a cascading failure simulation tool, named Incident Response Systems (IRS) [33], to capture the sequence of events during an emergency, leading to a voltage collapse. We model the power system behavior with different voltage based load shedding schemes (no undervoltage load shedding, manual and automatic) analyzing the impacts from a technical and economic perspective.

In the next section, voltage control strategies under emergency are briefly discussed, mainly focusing on different load shedding schemes as countermeasure. In section III, IRS will be introduced, highlighting the undervoltage load shedding model. Section IV illustrates a comparison among the different impacts of different types of undervoltage load shedding with reference to the Austrian grid.

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2. VOLTAGE CONTROL UNDER EMERGENCY

Voltage collapse in a power system indicates that the operation is beyond its capability for the existing conditions and contingencies. The main symptoms of voltage collapse are low voltage profiles, heavy reactive power flows, insufficient local reactive support, and heavily loaded systems. The consequences of voltage collapse often require long system restoration, which causes a huge amount of unserved energy to large groups of customers. The symptoms can be exploited by protective schemes to mitigate the collapse.

According to IEEE/CIGRE Joint TF report, "Definition and Classification of Power System Stability", the time frame for voltage stability problems varies from a few seconds to tens of minutes [34]. Voltage collapses in the long time frames are attracting much of the attention and recent investigations. These types of collapses usually occur because of loss of significant sources or loss of heavily loaded transmission capability. Simulation tools to study time dependent system response in longer time frames have only been relatively recently developed, while tools for transient analysis of power systems are very mature and widely used [35].

As one of the causes of voltage collapse is an excess of load for the given transmission system, load shedding is an effective measure and its application is increasing in large-scale power systems.

NERC's Operating Policy 6-Operations Planning [36] includes the following criteria in Section C-Automatic Load Shedding: "After taking all other remedial steps, a system or control area whose integrity is in jeopardy due to insufficient generation or transmission capacity shall shed customer load rather than risk an uncontrolled failure of components or the interconnection".

Most of power system cascading failures include low or very low voltage conditions. Voltage collapse can occur over a wide variety of time frames [35]. The voltage variation rate affects the types of countermeasures that can be put in place and it depends on time and voltage varying characteristics of the system elements like loads, automatic tap changing transformers, generator excitation controls, governor and turbine responses, protective relays, and other automatic or manual control actions.

Although several studies show that undervoltage load shedding is a very effective countermeasure in preventing voltage collapse, it may not be beneficial to all systems. For

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example, in systems with fast voltage decay, direct full load shedding is the only solution to prevent a larger scale blackout in the system.

Load can be shed either manually or automatically depending on the rate of voltage drop. If the time frame of the voltage drop is in the range of minutes, manual load shedding can be implemented in order to stabilize the system, the operator intervention may in fact be expected after some minutes. If, vice versa, voltage drop is faster, manual load shedding would be too slow to act timely.

2.1. Manual load shedding

In the case of manual load shedding, the TSO's operators should have preplanned guidelines and procedures to follow. Blocks of sheddable loads should be predefined and preprogrammed on the control system SCADA. The major disadvantage of manual load shedding is the burden that is placed on system operators, that have to quickly recognize arising voltage stability problems [35].

2.2. Automatic load shedding

If the voltage perturbation is caused by a single major event on the network, voltage drop is fast and manual load shedding cannot prevent voltage collapse. In this case undervoltage relays may be used to trigger automatic load shedding. There are two basic types of automatic UVLS schemes: decentralized and centralized. In a decentralized scheme, relays are installed at the loads which are needed to be shed in case of rapid voltage decay. When voltage conditions at these locations start collapsing fast, load assigned to that relay is shed. This is somehow like under frequency load shedding and it can be considered as one the automatic protections. In this scheme, automatic UVLS reacts directly to the measured voltage conditions in a local area. It drops several hundred megawatts of load in predefined blocks within load centers, triggered while local voltage drops to a designed level, say from 89 to 94%, with a several seconds delay. It sheds load in order to restore reactive power balance, to prevent voltage collapse, and to keep the voltage problem local when a fast voltage decay is occurring. In this case, interaction between manual and automatic load shedding is not a problem and if both systems coexist, the time delays of the automatic system should be short enough to prevent overlapping with the manual procedure [35].

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When the voltage collapse evolution is slow, relays at the low voltage side of a tap-changer transformer may not sense low voltages while transmission system voltages may drop excessively. The centralized schemes aim to protect system in case of slow voltage collapse (several minutes to one hour): all measurements are conveyed to, and all the decisions are taken by a central control center, undervoltage relays are installed at key system buses and trip information is transmitted to shed load at various locations [37]. In this case, interaction between manual and automatic load shedding may be a problem as the time scales might overlap.

The main problem connected to an automatic system is the appropriate setting of the devices, which means proper voltage thresholds and proper time delays. The undervoltage relays should not operate in case of temporary low voltage events which do not lead to collapse. For example, low voltages caused by load pickup or by normally cleared faults must be discriminated and the UVLS system should not be triggered. The UVLS scheme setting, including voltage thresholds, time delays and predefined loads to be shed in emergency, need to be coordinated with the other protection relays.

These countermeasures are suggested in the current NERC (North American Electric Reliability council) regulations and widely implemented in North American power systems [38].

3. CASCADING FAILURE SIMULATION

In this section, first we briefly introduce a simulation framework we implemented as a software tool: Incident Response System (IRS) [33], which chronologically simulates the sequence of post-contingency failures ("cascading failure") and the restoration actions on a time-frame scheme. More details on the specifications of this simulation framework and the modelled components of a power system can be found in the SESAME project deliverable named "System Specification of Decision Support System" [33]. As the focus of the paper is on cost-benefit analysis of manual and automatic undervoltage load shedding, then we explain how the manual and automatic undervoltage load shedding are modeled in this framework.

3.1 Incident Response System

A cascade occurs when there is a sequential tripping of numerous transmission lines and

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generators in a wide geographic area. It can be triggered by only a few initiating events we call “triggering events” which are materialized form of natural, accidental or malicious threats to power systems [21].

In the IRS (Fig 1), we modeled a large set of existing automatic countermeasures as well as human optimal operation decisions. The purpose is to model, evaluate and compare the effective countermeasures for system operators, especially the long-term investment; therefore, the observation windows we use are from several minutes to days. With such large observation window, dynamics are hardly observed. Therefore, all components are represented by a quasi steady-state model. Quasi steady-state means that each snapshot is solved by a steady state model, but the variation of some quantities (e.g. frequency, voltage, etc.) between different snapshots is also modeled. All common power system elements including generators, branches and loads are modeled as well as capacitor and shunt inductor banks, phase shifters, FACTS devices, DC lines, and pumped-storage stations. The system power-frequency characteristic for the entire system, including generator droop and load frequency response are considered. To model frequency control such as primary control, loads are modeled sensitive to frequency. The self-regulation of the load has been also applied assuming 1%/Hz [32], which means a load decrease of 1 % occurs in case of a frequency drop of 1 Hz. Voltage collapse is studied in steady state simulation using constant MVA loads having no voltage sensitivity, which may result in the most pessimistic outcome. As the simulation framework is mainly designed to perform a trade-off analysis to compare different countermeasures effectiveness under the same conditions (e.i. the most dramatic situation with respect to voltage violations), the analysis conclusion remains valid.

As human optimal decision making requires more time with respect to the system automatic reactions, IRS enables user to set a time before which only automatic protection schemes are considered in simulation. These actions mainly include: frequency control (including primary control, secondary control, reserved generation, and automatic/manual under frequency load shedding (UFLS)) , voltage control (including automatic voltage control (AVR) and automatic/manual undervoltage load shedding (UVLS)), component-wise protections (modeling under/over voltage relays for all the parallel-connected components, over current relays for all branches and generators under/over frequency

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relays), human non-optimal operational intervention, and system feasibility evaluation.

As soon as IRS reaches the predefined time in simulations – called second-stage reaction initiating time –, if no new equilibrium point is established, it first tries to find a feasible solution for the system by minimizing load shedding through optimization modeling and prioritizing loads. After establishing a new system equilibrium, it mainly aims to restore the system and the loads. It also implements the black start procedure if needed.

IRS is flexible to handle network islanding so that in case of system split due to line disconnections, all islands can be treated separately and simultaneously. Moreover, islands can get integrated during the restoration, depending on branches' re-closure time.

A scheduler is designed to schedule triggering events occurrence, all system time-dependent automatic protections, load curve following and modification of system element settings as a flexible model of human driving actions (like manual load shedding, generators operational status, etc.) as well as human optimal decision initiating time.

The evolution of the system status is observed in discrete time points called system snapshots. The time-points are provoked by user set intervals and special events during the simulation. Simulation end time as an input is also defined by user. The total unserved energy for this given amount of time is calculated by the software, and it can be translated into economic losses. Benefits of different types of countermeasures can then be evaluated comparing their implementation cost with the reduction of unserved energy cost.

As in this paper, we focus on analyzing the benefits of automatic undervoltage load shedding, in this section we focus on modelling different undervoltage load shedding schemes and shortly describe the undervoltage control module in IRS.

3.2 Modeled UVLS

The common voltage control measures, such as direct load tripping, generators Automatic Voltage Control (AVR), transformer automatic LTC action, LTC blocking, capacitor bank switching, SVCs, common voltage protection relays, are modeled in the IRS. In addition, in IRS, we modeled both manual and automatic UVLS, which will be briefly discussed here.

Manual load shedding may be required to backup the automatic scheme. To model the manual LS, the software is flexible to involve human intervention by predefining the

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voltage and load amount for a specific time after triggering events occurrence.

Since voltage collapse may happen suddenly, there might not be enough time for operator interventions to stabilize the system. Therefore, an automatic undervoltage load shedding scheme is needed as an effective means to rescue the interconnected systems and mitigate the voltage collapse effects.

Some existing automatic undervoltage load shedding application schemes are summarized in reference [39]. Some utilities such as Hydro Quebec and New Mexico installed centralized controller; some cases like Entergy and Southern Sweden applied UVLS function as part of EMS; and in some cases such as Puget Sound and Northeast Ohio decentralized U/V relays installed in substations were utilized.

It is not possible to find a generic load shedding scheme to be suitable for all systems; in some grids, shedding only a nominal amount of load in one step may be an enough remedy while in some others more extensive schemes using two or more levels of load shedding with corresponding multiple voltage pick-up points and time delays are needed. As well, for some power systems, centralized schemes might be more efficient.

In IRS, the implemented automatic UVLS scheme is a basic scheme which mainly models the decentralized type; however it can be customized by the user for individual regulated plans. The main characteristics of UVLS schemes are voltage threshold values, time delays, locations and amounts of load to be shed. No generic values are defined for these parameters by different regulations or standards and they all depend on individual systems. Nevertheless, having studied the implemented schemes, we found ranges of 0.85-0.95 for the voltage threshold value, 1-10 seconds for the time delay, and 5-20% for the amount of shed load as the most common setting values.

There are sometimes several shedding steps containing different load amounts, voltage threshold values or time delays. In our modeled UVLS scheme, these values can be predefined by user. IRS receives the bus information including the substations where the loads have relays for shedding by percentage, the voltage threshold value in which automatic UVLS is executed, time delay and amount of load to be shed in maximum 3 allowed steps. To run UVLS the transmission system voltage (bus voltage) are measured considering contingencies like line trips. As voltage conditions at these locations begin to collapse, load assigned to that relay is shed.

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4. IMPACTS ANALYSIS OF DIFFERENT SCHEMES

In order to analyze the benefits of undervoltage load shedding, we apply the IRS to a simplified model of the Austrian grid on which a contingency scenario is applied, which results in an outage in case no undervoltage load shedding is considered.

The Austrian base case model is extracted from an approximate model of the European interconnected system presented by Qiong Zhou and Janusz W. Bialek [40]. For the load flow model, only publically available data was used. The base power flow solution has been modified to ensure n-1 contingency compliance.

To extract and isolate the Austrian network from the European interconnected system we capture a snapshot of the transmission system operation status including power flow of tie lines between Austria and its neighboring countries. Then in order to model the tie-lines, equivalent generators are assigned to the neighboring buses which represent the imported/exported power from/to Austria. The equivalent generator capacity was set as the corresponding tie line capacity. In the test system, there are totally 39 generators among which 14 generators are tie-lines equivalent models, 49 buses, 114 branches (including 30 inter-ties) and 19 loads with a total consumption of 6793 MW and 1888.5 Mvar. The system total generation capacity is 19400.5 MW and ±16920.0 Mvar and actual in-service production is 6793.4 MW and 3649.2 Mvar.

The network data extracted from reference [40] mainly includes power flow related data, while some other technical parameters/settings such as protection settings, restoration time and costs, generation droop, etc., required for the IRS physical network model [33], are set according to previous studies [43].

The assumptions needed to design the scenarios (technical parameters, imminent natural threats, protection schemes, operator behavior in emergency situations) have been taken from the security project SESAME, whose outcome has been confirmed by the Austrian Regulator (E-Control). For the simulation of the load profile we use the Austrian load curve (24 values, time intervals of 1 hour), taken from Austrian Power Grid (APG) for 01-07-2010 [41], as the basic pattern to scale out the load curve for our test case. The active load of the test case was 6793.38 MW at 14:00, while the active load from the APG curve at the same time is 6246.93 MW, so we scale the APG curve by a ratio of 6793.38/6246.93 before using it in the simulation.

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In the designed scenario, we assume a flood as natural threat to the Austrian power grid which destroys one generator and 2 transmission lines (triggering events) at 14:20 (Fig 2).

We set 20 minutes after triggering events occurrence, operator starts making optimal decisions – explained in the previous section - and 5 minutes as the interval between two consequent captured snapshots of the system before arriving at the above-mentioned time. In order to reflect system instantaneous reaction or changes at the triggering events occurrence time, IRS represents two snapshots for the time 0^- and 0^+ (at $14{:}20^-$ and $14{:}20^+$). Loosing generators, disconnection of lines or loads outages are some examples of system sudden variations which result in different snapshots in terms of system status. The interval between two snapshots during operator optimal decision making simulation is set to 15 minutes however, when the system load changes (load curve values change every hour), the IRS automatically generates an additional snapshot (in the test case at 15:00 which is only 5 minutes after the previous one). Consequently, the system status evolution is described by 10 snapshots. In Table II a summary of important events/effects (defined in [33]) which happen during a time interval are briefly mentioned at the end of each interval.

For the undervoltage protection relays, 0.83 pu is assumed as the threshold and 9 minutes as tolerance delay after which the load is totally shed in case voltage is not corrected. The voltage threshold for the automatic UVLS relays is set 90% of the normal value based on the implemented UVLS protection relays in Puget Sound, Washington, US, as it is one of the most typical schemes [31]. According to this guideline, “the relays operate when the voltage is below a set threshold, for a minimum time duration”. Considering the time needed for human decision, we assume the manual load shedding happens between 5 to 10 minutes after the contingency. Therefore, the effects can be captured at the end of second time interval, i.e. 10 minutes after the event.

The post-contingency behavior of the system during one hour is simulated by IRS considering 3 cases: a base case without any kind of undervoltage load shedding, a case with manual undervoltage load shedding and finally a case with deployed automatic undervoltage load shedding. Besides technical effects such as voltage magnitude profiles of some buses, the impact on the system in terms of unserved energy is assessed and compared.

In the simulated scenario voltage drop is one of the main effects of the

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triggering/cascading events, which causes cascading failures such as line trip due to overcurrent. Fig 3 presents a comparison among the 3 different cases in terms of voltage magnitude evolution in the buses where low voltage is observed (A-10, A-11, A-12, A-13, A-14, A-16, A-18 and A-30 in the Austrian grid [40]).

Simulation results for the base case with no UVLS show the voltage drops in some buses in the center of network which lead to load interruption and line trip due to undervoltage and overcurrent protection relays reaction. This eventually causes power outage in most parts of the network (Fig 4) after 1 hour.

In the case with manual UVLS, 10 minutes after severe low voltage observation, the operators shed the interruptible portion of the loads (18% of total loads supplied from buses A-13 and A-14). As low voltage is more wide speared than only these 2 buses and this load shedding cannot correct voltage sufficiently, 5 minutes later we see the 2 loads are totally disconnected as undervoltage protection relays do not allow violation persists for more than 9 minutes (violation is observed at 14:25).

In the case with automatic UVLS, some undervoltage relays are assumed to be installed in central buses of the Austrian grid to monitor substation bus voltage, and to trip selected breakers at that bus. The relays operate when the voltage is below 90% of the normal voltage magnitude and shed 5% load at each step.

Table II summarizes some general descriptive information of the 10 snapshots for the 3 cases.

System post-contingency evolution in the 3 different cases results in 3 different unserved energy values. Fig 5 depicts total served load amounts during the cascading evolution and Fig 6 provides a comparison of all 19 loads trend in one glimpse. Vertical axis presents active served loads in MW.

The 3 cases (without/with manual/with automatic UVLS) can be analyzed comparing the different unserved energies with the UVLS scheme implementation cost and extra operational costs due to increasing generators power output and load shedding cost. In order to monetize the impact of the UVLS on the level of security of supply, the total costs can be compared.

We calculate the cost of unserved energy according to the general formula, Cu= G/E where Cu is the cost of unserved energy, G is the GDP and E is the domestic electricity

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consumption: G and E values for year 2010 are taken from key statistics 2011 report of the Austrian regulator (E-Control) [42]. Considering the calculated cost of unserved energy as 3800 €/MWh, the value of the economic loss in our case study would be 16,087,680 € without UVLS, 5,246,280 € with manual UVLS and 3,091,300 € with automatic UVLS. Neglecting the small amount of extra operational cost, 12,996,380 € (the economic loss difference between the case without UVLS and the case with automatic UVLS) and 10,841,400 € (the economic loss difference between the case without UVLS and the case with manual UVLS) are the avoided costs thanks to the implementation of the automatic or manual UVLS schemes as countermeasures. For a cost/benefit analysis, the avoided costs can be compared with the cost of UVLS implementation.

It should be noted that, in this example, the analyzed time frame is 1 hour, in which most of the loads cannot get restored in the base case without UVLS. This means that until the end of system recovery process - which takes much more time than 1 hour and is not simulated here - the amount of unserved energy would be much higher, and should be considered for the cost-benefit analysis.

5. CONCLUSION

Voltage collapse has been a critical issue in many recent blackouts. According to the results of the cost-benefit analysis proposed in this paper, UVLS is a key-measure, to arrest voltage collapse, especially during extreme contingencies. UVLS schemes are being widely installed to bulk power delivery substations in the power networks supplying to densely populated areas especially in the US. In the European countries instead, the UVLS has been suggested but not actually implemented. This study can technically and economically support the recommendations from regulations for UVLS implementation and deployment.

The benefits of applying UVLS can be observed in both technical and economic aspects. From the technical point of view, the UVLS can prevent power outages due to the fast voltage decay and accelerate voltage recovery. From the economic point of view, it can avoid a large amount of societal losses; as has been shown by the simulated case, the saving can be up to 67 % and 81 % of total economic loss by applying manual and automatic UVLS respectively.

In case of fast evolution of voltage collapse and insufficient time for operators to apply a

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wise quick decision, Automatic UVLS is proved to be a cut above Manual UVLS.

It is strongly recommended that the UVLS should be implemented in the European transmission systems which can greatly mitigate the risks of voltage collapse and blackouts, with associated long term economic savings.

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Collected Figures Captions:

Fig 1 High level flowchart of IRS framework

Fig 2 Austrian grid with the triggering events at 14:20 on 01-07-2010

Fig 3 Voltage magnitude [p.u.] of some buses in the 3 simulated cases

Fig 4 System snapshot at 15:20 (simulation end time) in case with no UVLS

Fig 5 Total served load during the cascading evolution in the 3 cases

Fig 6 comparison of load shedding in the 3 cases

Collected Tables Captions:

Table I BLACKOUTS INVOLVING UNDERVOLTAGE IN EU

Table II A DESCRIPTIVE SUMMARY OF SYSTEM SNAPSHOTS DURING 1 HOUR STUDY INTERVAL

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Table I – BLACKOUTS INVOLVING UNDERVOLTAGE IN EU

Country and Area	**Date**	**Main references**
France – Eastern part of the country	19/12/1978	[4]
France – Western part of the country	12/01/1987	[4]
France – Western part of the country	26/12/1999	[5],[6],[7]
UK – London Southern area	28/08/2003	[8],[9]
Croatia (Southern part of the country) and Bosnia Herzegovina	12/01/2003	[10],[11],[12]
Sweden Southern part of the country) and Denmark (Eastern part of the country)	23/09/2003	[13],[14],[15]
Italy – All the country except for Sardinia	28/09/2003	[16],[17]
Norway – Bergen, larger part of Horland and northern parts of Rogaland	13/02/2004	[13],[18],[19]
Greece – Athens area	12/07/2004	[13]
Poland	26/06/2006	[20]

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Table II A DESCRIPTIVE SUMMARY OF SYSTEM SNAPSHOTS DURING 1 HOUR STUDY INTERVAL

Snapshots		Description of snapshots		
Clock Time	*Time [min]*	**Without UVLS**	**With Manual UVLS**	**With Automatic UVLS**
14:20	*0^-*	System normal operation	System normal operation	System normal operation
14:20	*0^+*	1 generator and 2 lines trip	1 generator and 2 lines trip	1 generator and 2 lines trip
14:25	*5*	Sever voltage drop in some buses (2 buses less than 0.83, 4 buses less than 0.9), voltage protection relays sense the violation	Sever voltage drop in some buses (2 buses less than 0.83, 4 buses less than 0.9), voltage protection relays sense the violation	Sever voltage drop in some buses (2 buses less than 0.83, 4 buses less than 0.9), voltage protection relays sense the violation
14:30	*10*	Voltage drop in some buses (2 buses less than 0.83, 4 buses less than 0.9), overcurrent in 2 lines	18 % of the loads on 2 buses as their interruptible portion are shed manually, voltage drop in 6 buses	5% automatic undervoltage load shedding on 6 buses (voltage threshold 0.90 pu), voltage correction, no relay threshold violations
14:35	*15*	Tripping 2 lines, power outage in 2 loads by protection relays action	power outage in 2 loads by protection relays action since load shedding could not correct voltage well, no overcurrent, voltage correction	5% automatic undervoltage load shedding on 4 buses where still voltage magnitude is below 0.9 pu
14:40	*20*	Under frequency load shedding in some loads, severe low voltage observation in some central buses (more than 5 buses less than 0.83)	Load restoration in 2 buses, voltage drop in 5 buses (however protection relay threshold, 0.83, is not violated)	5% automatic undervoltage load shedding on 3 buses where still voltage magnitude is below 0.9 pu, start bringing the network voltage back to its normal level
14:55	*35*	Tripping of many lines, widespread power outage (85 % unserved load), the lines' tripping caused the separation of the network	Load shedding minimization bringing system to a feasible operational point	Voltage correction, no more loads are shed, frequency gets back to the reference value (50 Hz)
15:00	*40*	Still 85 % of system total load is not supplied	Voltage correction, load restoration	re-dispatching of the power, System feasible
15:15	*55*	Demand decreases to follow load curve in the supplied island (west of Austria), the rest of network still in blackout	No voltage/current violation, re-dispatching of the power, load decrease following load curve, most of the load are restored to the full demand	No voltage/current violation, re-dispatching of the power, load decrease following load curve, most of the load are restored to the full demand
15:20	*60*	The same status as previous snapshot ***4233.6*** *MWh total unserved energy*	More loads are restored to the full demand, ***1380.6*** *MWh total unserved energy*	More loads are restored to the full demand, ***813.5*** *MWh total unserved energy*

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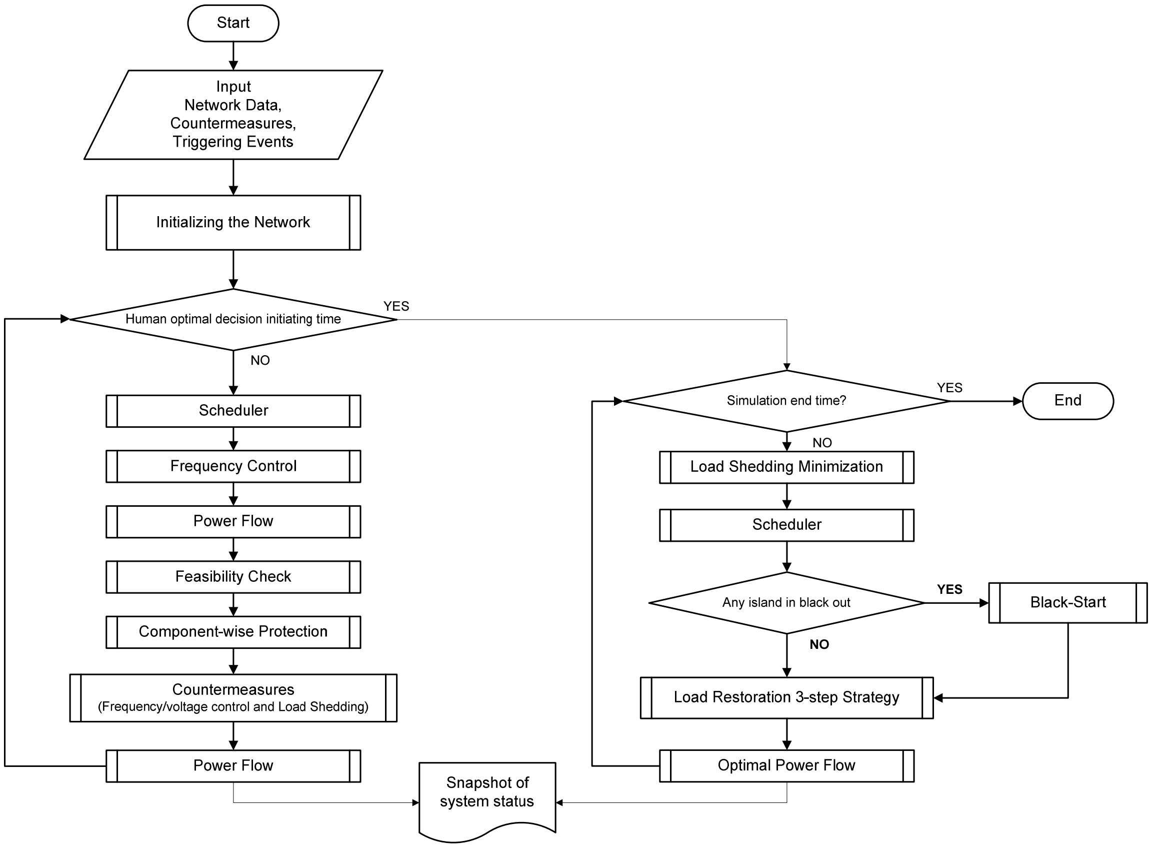

Fig 1 High level flowchart of IRS framework

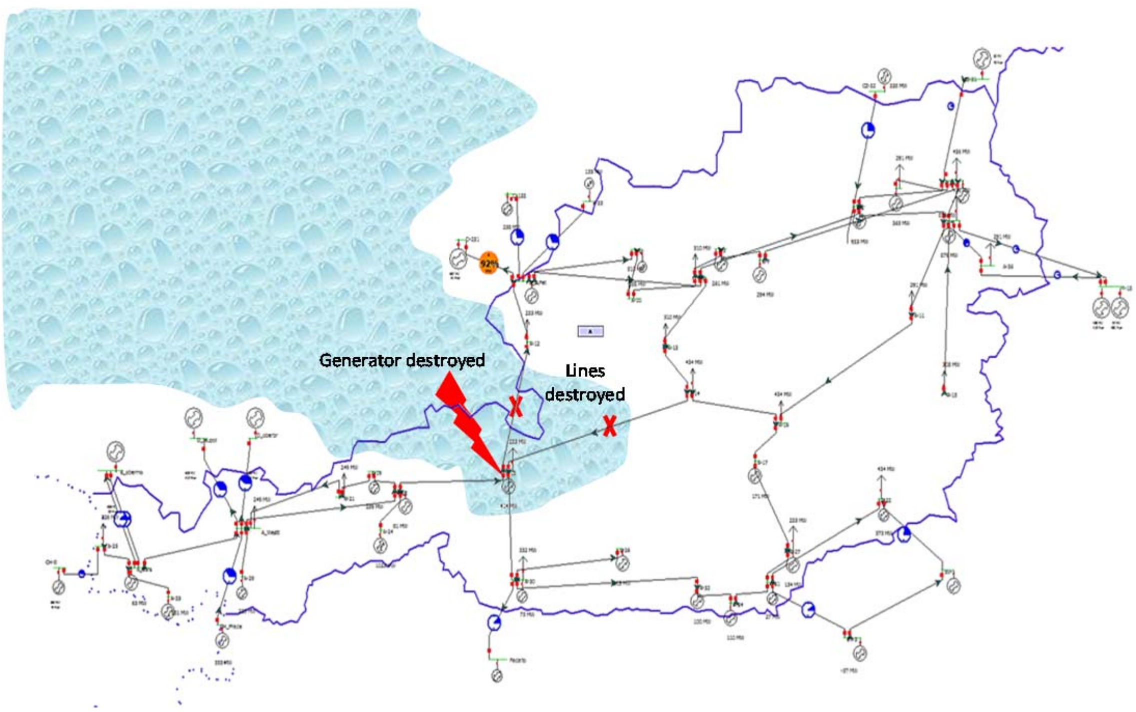

Fig 2 Austrian grid with the triggering events at 14:20 on 01-07-2010

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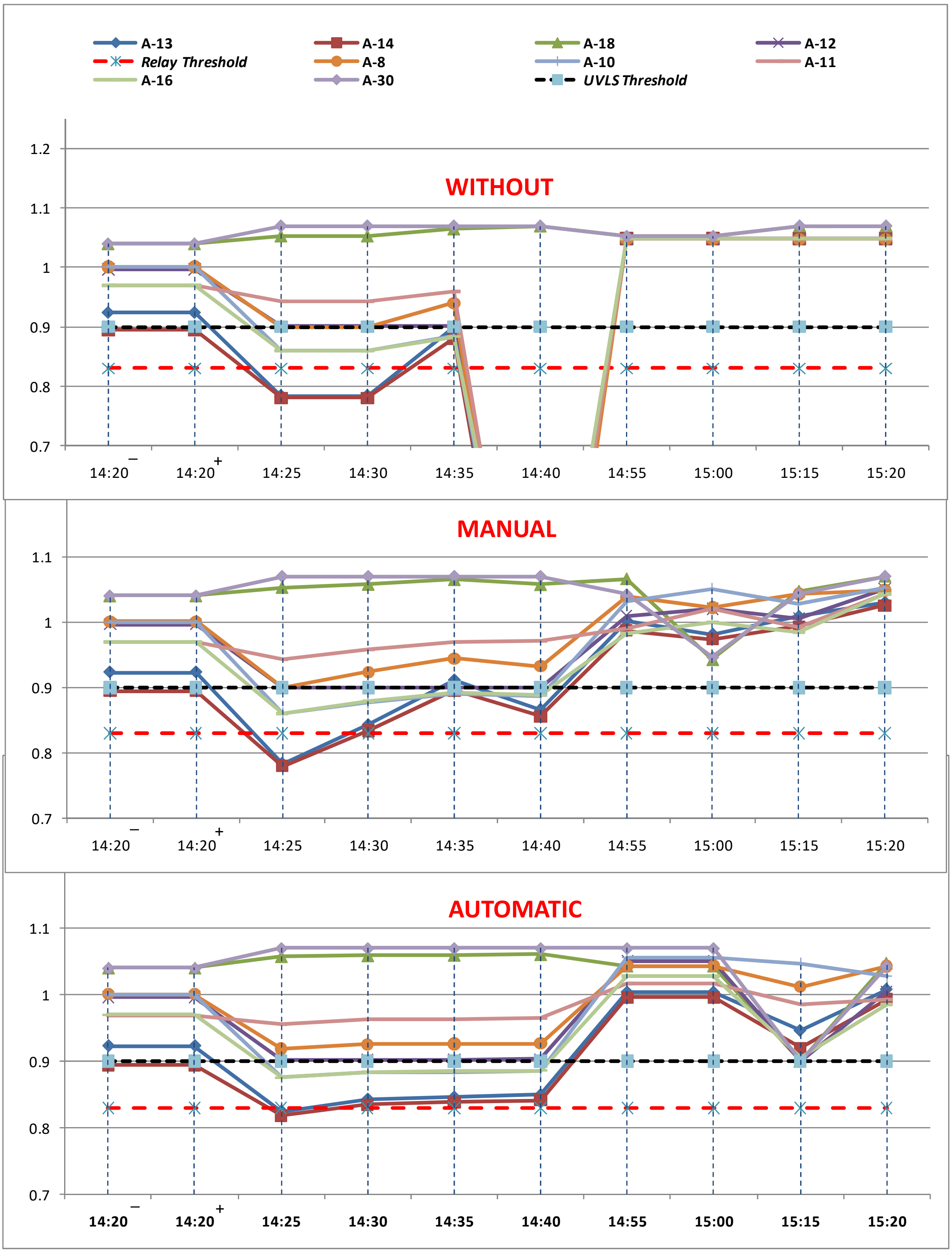

Fig 3 Voltage magnitude [p.u.] of some buses in the 3 simulated cases

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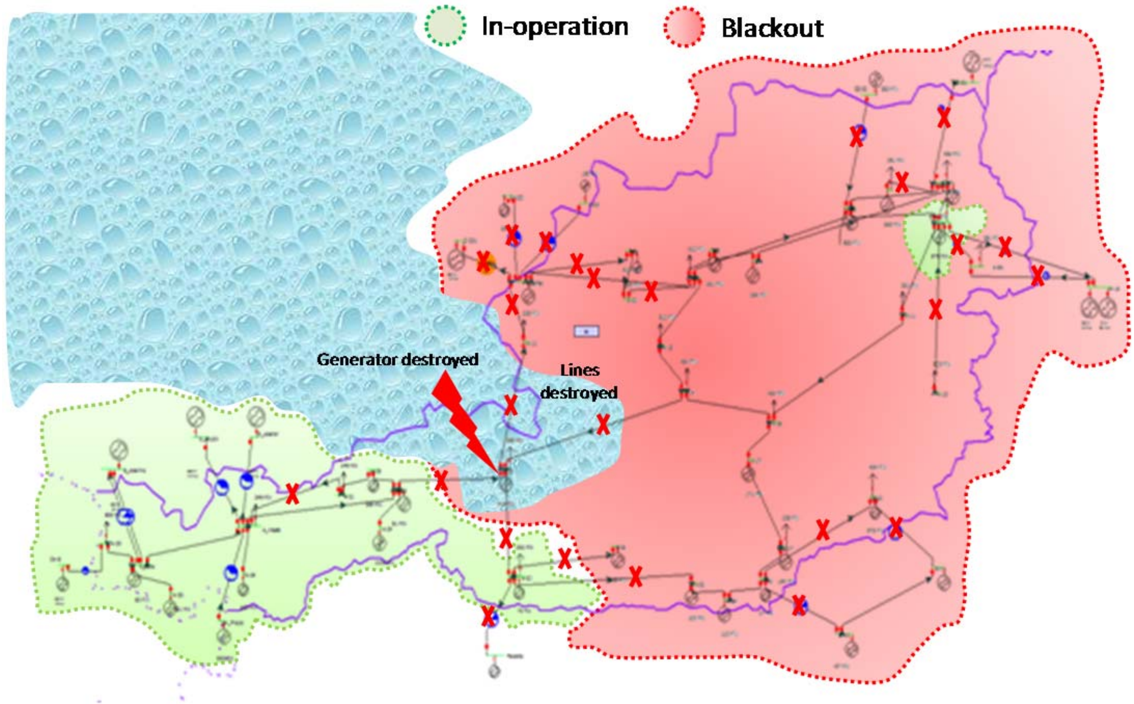

Fig 4 System snapshot at 15:20 (simulation end time) in case with no UVLS

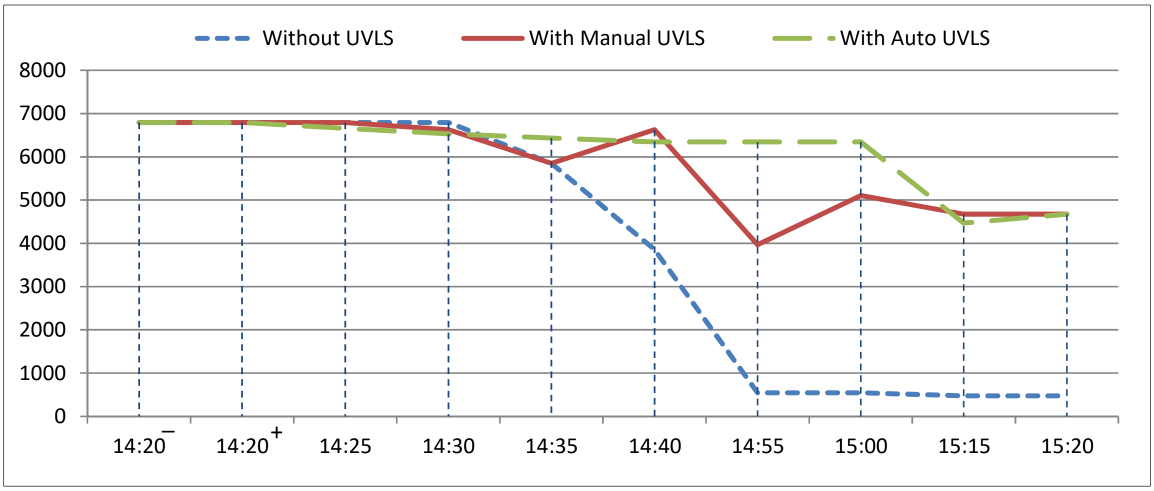

Fig 5 Total served load during the cascading evolution in the 3 cases

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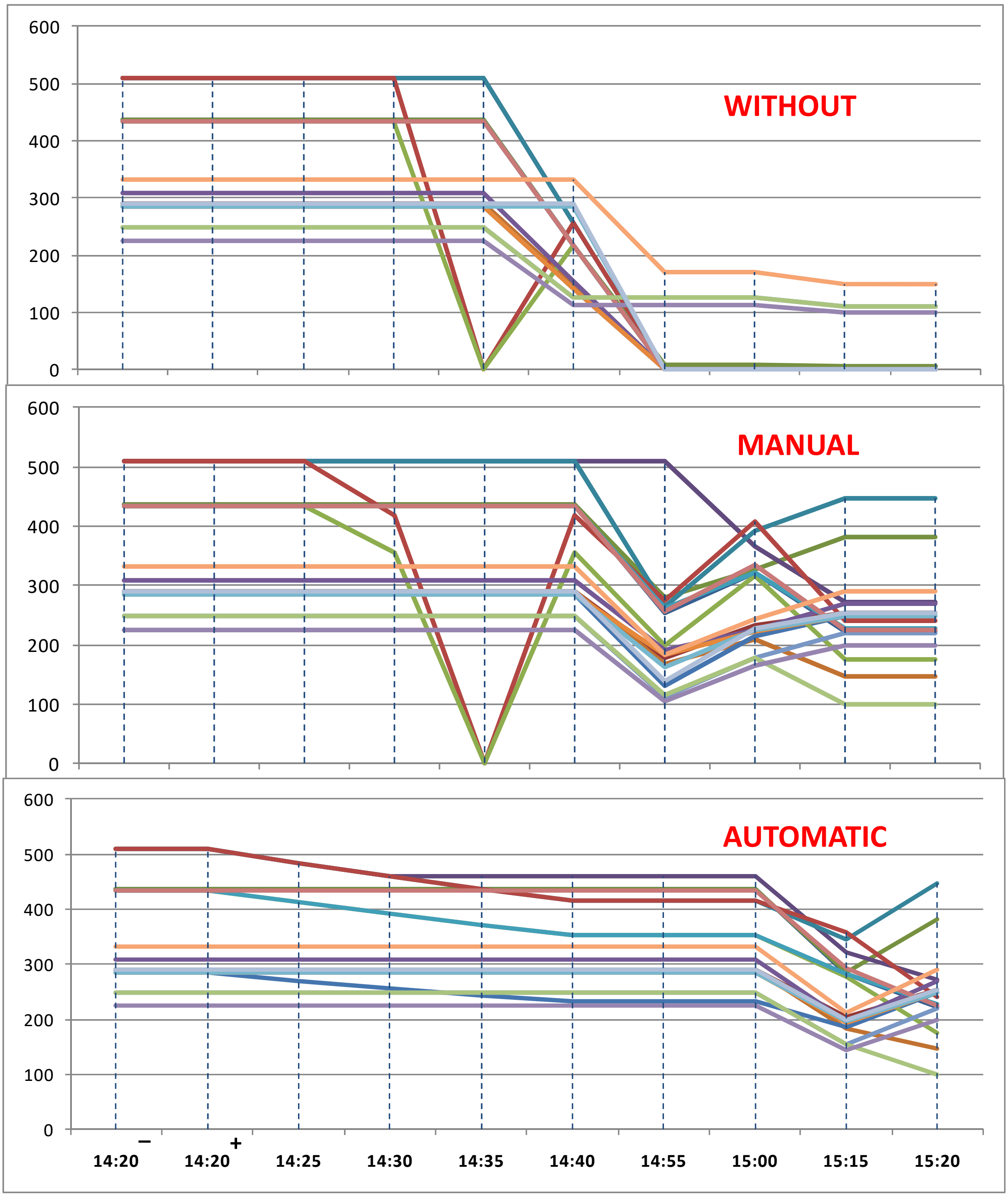

Fig 6 comparison of load shedding in the 3 cases

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