INVESTIGATION OF A LOCAL INDICATOR OF VOLTAGE EMERGENCY IN THE HELLENIC INTERCONNECTED SYSTEM

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Abstract – In this paper we evaluate the performance of a proposed local indicator of voltage emergency for a simulated unstable contingency of the Hellenic Interconnected System identified through the on-line VSA application for the summer peak of 2007. The effect of deadbands and tap range limits in delaying the emergency alarm issued is examined. The area mostly affected by the instability is identified through the proposed algorithm and a simple load-shedding scheme sufficient to avert the collapse is suggested.

Keywords: Voltage stability, emergency detection, load shedding, system protection schemes.

1 INTRODUCTION

System protection schemes (SPS) against voltage collapse include in many cases undervoltage load shedding (UVLS) [1-4]. These schemes are based on the measurement of low voltages in the transmission system and require extensive tuning, so that they act only on real emergencies. On the other hand, an SPS against voltage collapse can be complemented by a real-time emergency indicator able to signal out a critical condition. This would certainly help to further automate corrective emergency actions. To this purpose, a Local Indicator of Voltage Emergency Situations (LIVES) proposed in [5] is applied in this paper to the Hellenic Interconnected System operated by the Hellenic Transmission System Operator (HTSO).

The Hellenic Interconnected System is characterized by bulk North to South power transfers leading to voltage stability problems and has experienced a blackout of its southern part, due to voltage collapse, in July 2004. Since then many upgrades were undertaken, however, a voltage instability threat is always present and an on-line Voltage Security Assessment (VSA) tool has been installed at the National Control Center of HTSO [6].

This paper presents indicative results obtained by simulation of an unstable contingency that was identified by the VSA on-line tool during the summer of 2007. The analysis includes the investigation of LIVES alarms produced in this case, as well as the evaluation of possible countermeasures for instability containment, such as local load shedding, based on LIVES alarms.

In the next Section the LIVES algorithm is reviewed. Section 3 presents on-line VSA results for 2007 peak load of the Hellenic System, while in Section 4 the LIVES algorithm is applied for the case of an unstable contingency. Section 5 concludes the paper.

2 LOCAL INDICATOR OF VOLTAGE EMERGENCY SITUATIONS (LIVES)

2.1 Stability of a multi-LTC system

Let us consider in this Section a power system whose long-term dynamics are those of the Load Tap Changers (LTC) of bulk power delivery transformers. In the simulations performed in later Sections other long-term devices, such as OverExcitation Limiters (OELs) will be considered.

As shown in Fig. 1, the variable ratio r_i is considered to be on the primary (transmission) side and the LTC is controlling the secondary (distribution) voltage V_i. Load is considered voltage dependent. Short-term dynamics are assumed to be stable, as only long-term voltage stability issues are addressed.

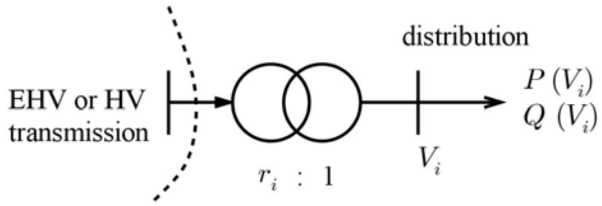


Figure 1: Transformer LTC feeding voltage-sensitive load

Let m be the number of LTC-controlled loads. To facilitate the analysis, we assume that all LTCs have the same tap ratio step Δs and period of operation T. The general case of different tap step and time delay for each LTC can be handled as described in [5].

The LTC mechanisms are discrete with a voltage deadband. Thus at every period of operation T the i-th transformer ratio changes according to the difference equation:

$$r_i(kT) = r_i(kT-T) + \Delta r_i^k \quad (1)$$

with $$\Delta r_i^k = \begin{cases} \Delta s & \text{if} \quad V_i > V_i^{\max} \\ 0 & \text{if} \quad V_i^{\min} \le V_i \le V_i^{\max} \\ -\Delta s & \text{if} \quad V_i < V_i^{\min} \end{cases}$$

where V_i^{min} and V_i^{max} are the lower and upper deadband limits.

The long-term stability of the system is linked to the Jacobian of secondary voltages with respect to tap ratios:

$$\mathbf{A} = \left[\partial V_i / \partial r_j\right] \qquad i,j = 1,...,m \qquad (2)$$

The vector of secondary voltage changes at each step k under the above assumptions is given approximately by the linearized expression:

$$\Delta \mathbf{V}^k = \mathbf{A}\,\Delta \mathbf{r}^k \qquad (3)$$

where $\Delta \mathbf{r}$ is the vector of tap ratio changes.

Stability of this linearized discrete system is guaranteed if all voltage errors outside the deadband decrease at each step. A necessary condition to achieve this correction is that the diagonal elements a_{ii} of $\mathbf{A}$ are negative, so that each tap change performed according to (1) will decrease the error at the corresponding bus. However, this condition is not sufficient for stability because the other taps may counteract this error correction. If, however, matrix $\mathbf{A}$ is diagonally dominant with negative diagonal elements, the error correction achieved by the diagonal term cannot be counteracted whatever the direction of movement of the other taps. We thus obtain the following sufficient stability condition, originally derived in [7]:

$$a_{ii} + \sum_{j \neq i} \left| a_{ij} \right| < 0 \qquad i,j = 1,..,m \qquad (4)$$

Usually the off-diagonal elements are positive (as will be discussed later on), so that the absolute sign can be dropped in (4).

Let us now assume that after a severe disturbance all voltages (at least in the area of interest) are below deadband. As a consequence, each LTC will react in every period T by decreasing its ratio by the amount Δs. Under these conditions, the change ΔV_i made to voltage V_i at step k is given by:

$$\Delta V_i^k = -\Delta s \sum_j a_{ij} = -\Delta s (a_{ii} + \sum_{j \neq i} a_{ij}) \qquad (5)$$

The similarity between the expression in parentheses and the sufficient stability condition (4) suggests that the change in controlled voltage could be used to monitor stability. However, before proceeding we should examine the sign of sensitivities, in order to remove the absolute value from (4).

As discussed above, the diagonal elements a_{ii} must all be negative for stability. This condition generally holds in normal loading conditions, for which each ratio r_i is above the value maximizing V_i with all other taps being considered constant. When this maximum is reached a_{ii} becomes zero, and for even lower taps it changes sign. Clearly, maximizing V_i results also in maximum power consumption, if the power sensitivity to voltage is positive, which is the usual case. Note again that this maximum refers to all ratios except the i-th one being constant.

Assuming that all loads are non-capacitive, the sign of an off-diagonal sensitivity a_{ij} can be indirectly assessed as follows: the increase in the load consumed at bus j brought about by a decrease of ratio r_j will result in a decrease of transmission voltages. If all other taps remain constant, this will result in a decrease of the secondary voltages of the corresponding LTCs.

When these conditions hold, the sufficient stability condition (4) becomes simply:

$$a_{ii} + \sum_{j \neq i} a_{ij} = -\frac{\Delta V_i^k}{\Delta s} < 0 \;\Leftrightarrow\; \Delta V_i^k > 0 \qquad i = 1,..,m \;(6)$$

which suggests that, after a large disturbance, instability can be detected locally by simply monitoring an LTC-controlled voltage. Note that the violation of (4) is also a necessary condition for matrix $\mathbf{A}$ to become singular [5], thus instability can be detected through (6) before the bifurcation surface is encountered. As we will see in the case study, however, in practical situations, especially when instability is marginal, the identification of the violation of (6) can be delayed due to deadbands and LTC control range limits.

2.2 Principle of LIVES operation

The Local Identifier of Voltage Emergency Situations (LIVES) is based upon the detection of secondary (controlled) voltages going through a maximum during the post-disturbance evolution, while still below deadband. It could be easily incorporated into the control logic of LTCs and uses only information available in the LTC, namely secondary voltage, deadband limits and time delays between tap changes. In this paper we will use a method of emergency identification based solely on (6). The effect of measurement noise and a filtering scheme based upon moving average are investigated in [12].

LIVES logic is very simple: to initiate the detection, the LTC must be active (i.e. not limited, nor blocked), and the controlled voltage must be below its lower deadband limit. As a consequence, LIVES is reset each time the secondary voltage is restored within the deadband and becomes inactive after the LTC has exhausted its tap ratio range.

The secondary voltage values relative to successive tap changes are compared through:

$$\Delta V_i^k = V_i(kT) - V_i[(k-1)T] \qquad (7)$$

According to (5), in a system whose dynamics consist only of LTCs, a secondary voltage drop after one period of LTC operation means that the sum of the corresponding row of the long-term state matrix $\mathbf{A}$ has crossed zero and thus the sufficient stability condition is violated.

However, in a real system other events (such as generator switching under overexcitation limit) occur, which result in voltage drops that are not due to the action of LTCs. Thus, in a real system, a single voltage drop after a period of LTC operation is not a sufficient indication of the violation of (6). Thus, in order to issue a voltage emergency alarm an additional delay is necessary to ascertain that secondary voltage is dropping due to LTC actions.

To this purpose, we specify in this paper that ΔV_i^k must be negative for two successive values of k to detect an emergency situation. The overall delay for instability detection is in the time frame of two LTC periods of operation, roughly around 20 s, which is considered acceptable for emergency control against long-term voltage instability.

Of course it remains possible that random events cause two successive voltage drops within two periods of LTC operation. It could be argued, however, that in such a situation the system would be sufficiently weakened by these events to justify an emergency action.

3 HELLENIC INTERCONNECTED SYSTEM

3.1 System Description

The Hellenic Interconnected System serves mainland Greece and some adjacent islands. The main production center is located in the northwest part of the country, close to lignite mines, while the main center of consumption lies in the South including the metropolitan area of Athens. The transmission system operates mostly at the levels of 400 kV and 150 kV.

The geographical distance between generation and consumption leads to bulk transmission in the North-South direction. This transfer is continuously increasing due to the development of yearly peak loads (mainly in the South), which occur during the summer period and the difficulties encountered in building new transmission facilities. Thus, on various occasions the Hellenic System has faced critical operational conditions in the form of voltage instability.

Network reinforcements completed after the 2004 blackout [8] have considerably increased the loadability of the system, as shown in [6]. Further projects involving the installation of new generation have also been completed since.

3.2 On-Line VSA using QSS Simulation

Apart from system reinforcements, an on-line Voltage Security Assessment (VSA) application [9] has been installed in 2005 in the Control Center of HTSO. The on-line VSA is currently in operation, using data validated by the 2004 blackout simulation [8], and provides security margin information and loadability limits periodically, or upon request.

The computations performed within the VSA application are based on Quasi Steady-State (QSS) simulation, a fast time-domain method well suited to the analysis of long-term voltage stability phenomena [10]. The QSS approximation relies on time-scale decomposition. The essence of this method is that faster phenomena are represented by their equilibrium conditions instead of their full dynamics. This greatly reduces the complexity of the resulting model and hence provides the computational efficiency required to meet the constraints of the on-line application.

This method, which has been validated with respect to detailed time simulation, offers better accuracy and richer interpretations than simple methods based on load flow equations. Under the QSS approximation, the short-term dynamics of a synchronous generator, its governor and its Automatic Voltage Regulator (AVR), are replaced by nonlinear algebraic equations [10], which account for the generation saturation, the AVR steady-state gain and the speed droop. These nonlinear equations are solved at each time step, together with the network ones. QSS simulation reproduces the long-term dynamics of LTCs discussed in the previous section, but also includes models for OELs, automatically switched shunt compensation, other protection devices, etc. This simulation takes into account the delays between transformer tap changes, before a synchronous machine is switched under field current limit, etc.

As the QSS simulation is readily available from the on-line VSA application, it was convenient to carry out first tests on the proposed LIVES algorithm with this tool, even though tests on detailed models (with simulated measurement noise, etc.) are essential for a future application.

3.3 On-line VSA Results for 2007 Peak Load

As a result of continuing system upgrades and reinforcements, the overall voltage security of the Hellenic Interconnected System is much improved compared to the recent past. In the Summer of 2007 the total system load peaked above 10500 MW, which is a new historical maximum of the Hellenic System. On this day the system faced voltage security problems only with respect to the most critical contingencies involving significant loss of generation in Athens and Peloponnese regions.

In the region of Athens the major concern is the double contingency leading to the loss of both circuits of the 400 kV line serving two combined-cycle units with a total generation of 955 MW located at Lavrio Thermal Power Plant (TPP). This contingency appeared to have zero security margin, as monitored through the on-line VSA for the peak loading conditions of July 23rd, 2007.

No.	Name	SOL (MW)
289	LINE_CON_KTHES-SCHOLAR.1	0
149	GEN_CON_MEGALO_2.GEN4.UN	0
359	LINE_CON_MOURT-MESOG.1	0
321	LINE_CON_KYL-ZAKYN.1	0
234	LINE_CON_PTOL-KOZ.1	0
134	GEN_CON_K_LAVRIO.CC5.GFIC.UN	0
177	LINE_CON_ARG2-ARG1.1	0
50	DLINE_CON_ PELO-EPIR	109
143	GEN_CON_MEGALO1.GEN1.GEN2.	133
93	GEN_CON_IRON_K_LAVRIO.GFIC.	148
127	GEN_CON_ KOMO.GFIC.UN	195
70	DLINE_CON_MEGA2-PYRG	203
57	DLINE_CON_KTHES-EVOSM	219
	All others	>200

Table 1: Secure Operation Limits (SOLs) for July 23, 2007

Note that for this contingency, as well as for similar critical contingencies in Peloponnese, event-driven SPSs involving load shedding have been designed and put in operation [11]. The Secure Operation Limits (SOLs) [10] for the peak of this specific day (close to 1:30 pm) are shown in Table 1. As seen in the Table, contingencies no. 149 (loss of a 300 MW unit in Peloponnese) and the double contingency involving Lavrio TPP that was described above (no. 134) have zero security margins. The other contingencies shown in Table 1 with a zero margin refer to weak parts of the network and have only local impact [6,9].

The voltage evolution of the most affected transmission bus in the system for the simulated contingency 134 is shown in Fig. 2. The simulation was performed by the on-line VSA software (program ASTRE), which is using the QSS simulation approach. As seen, the ultimate outcome of the contingency would be a voltage collapse at simulated time t=240s. The collapse in this sense is due to the loss of short-term equilibrium of the system.

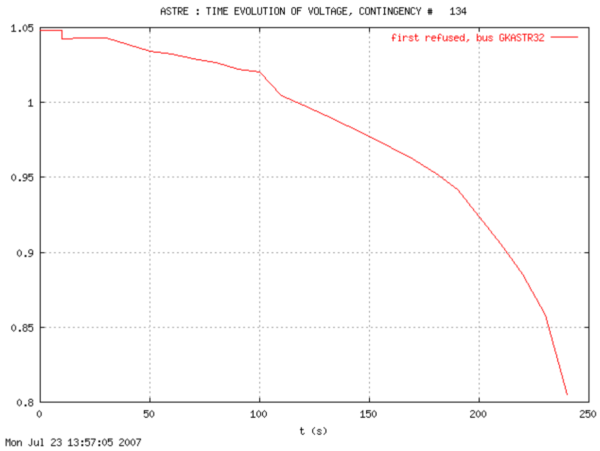


Figure 2: Voltage Evolution for contingency 134

4 APPLICATION OF LIVES ALGORITHM

In this Section we investigate the performance of the above-described LIVES algorithm for the specific simulated contingency no. 134 of July 23, 2007 as a first attempt to assess whether this scheme has relative merits with respect to the event-driven SPS.

As stated above, aspects relative to noise and filtering techniques [12] will not be addressed here. However, other real system aspects, such as the effect of deadbands and hard limits on LTC regulation range will be investigated in some detail.

Two approaches will be used. First the buses where LIVES would give a timely alarm are determined and then the effect of load shedding following the alarm is investigated taking into account LTC hard limits and also generator armature current constraints.

4.1 Determination of buses for alarm monitoring

During the computation of SOLs, the hard limits on LTCs are artificially suppressed, so as to allow full power recovery for all voltage sensitive loads. Thus, the response of Fig. 2 is drawn under this assumption (LTC limits neglected).

In this subsection we follow the same approach. The simulation was repeated off-line with increased data accuracy and the collapse was found to occur at 280 s. At the same time, LIVES algorithm was executed for all LTC transformers using the criterion of voltage recovery as explained in Section 2.2.

The results in terms of the timely alarms, together with the corresponding simulation time that they were issued, are shown in Table 2. As seen, in 10 buses the LIVES alarm is issued 20 seconds before the collapse, whereas in another 15 distribution buses the alarm is issued 10 seconds before the collapse. In 17 other buses (not shown in Table 2) the alarm is issued at 280s. This is considered too late for taking any corrective action.

No.	Bus	Time	Area
1	GTRICH52	260	West
2	GAETOL51	260	West
3	GAETOL52	260	West
4	G1PATR51	260	Peloponnese
5	G2PATR51	260	Peloponnese
6	G3PATR51	260	Peloponnese
7	GAEGIO51	260	Peloponnese
8	G1PATR52	260	Peloponnese
9	G3PATR52	260	Peloponnese
10	GPTIT_31	260	Peloponnese
11	GTRICH51	270	West
12	GVZPAT51	270	Peloponnese
13	GXILOK51	270	Peloponnese
14	GXILOK52	270	Peloponnese
15	GKRANI51	270	Peloponnese
16	GLECHE51	270	Peloponnese
17	GLECHE52	270	Peloponnese
18	GAMALI51	270	Peloponnese
19	GKIPAR51	270	Peloponnese
20	GPYRGO51	270	Peloponnese
21	G2PATR52	270	Peloponnese
22	GKIPAR52	270	Peloponnese
23	GPYRGO52	270	Peloponnese
24	GZAKIN51	270	West
25	GZAKIN52	270	West

Table 2: LIVES alarms for contingency 134 of July 23, 2007

It the last column of Table 2 the area of the bus, where the alarm was issued is shown. Figure 3 shows the significant details of the connections of Peloponnese peninsula in the case considered. In particular, a small part of Western Greece was connected radially through two 150 kV submarine cables to Peloponnese and was disconnected from the rest of the system at Kastraki Hydro-Electric Plant (HEP). This topology was selected in order to achieve better control of the flow through the submarine cables.

It is worth noting that even though the disturbance originated in the area near Athens the alarms are issued in the Northwest part of Peloponnese, the island of Zakynthos and the part of Western Greece connected to

Peloponnese. The ultimate result causing the loss of equilibrium in the QSS simulation is the loss of synchronism of the Kastraki HEP unit feeding Peloponnese (Fig. 3).

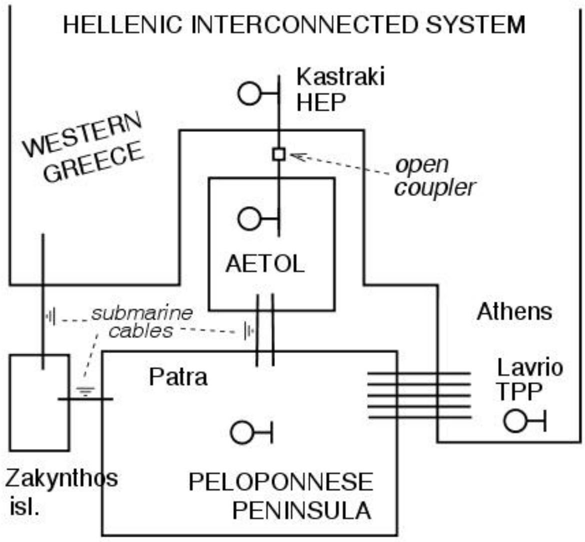


Figure 3: Peloponnese connections

This result may have useful consequences for redesigning protection systems against this contingency. Indeed a decentralized system based on LIVES monitoring could in principle be able to set the trigger for a local load shedding in the area of Patra that could avert an imminent voltage collapse.

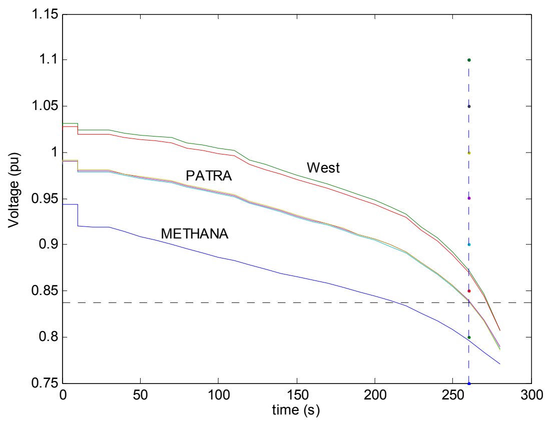


Figure 4: Voltages in Peloponnese and Western Greece

However, the effect of LTC limits has still to be assessed. This is done in the next subsection. Note also that the voltage level at transmission buses could also be used for triggering a local protection. As an example consider the voltage responses of some key transmission buses in Peloponnese and Athens area shown in Figs 4 and 5.

As seen in these figures, at the time the LIVES alarms were issued, transmission voltages in Patra and Athens are already below 85%. Note however, that even in other buses (not directly affected by the instability in question), as in Methana (East Peloponnese) voltages are even below 80%. In the Hellenic System many instances of low voltages, not leading to collapse, have been experienced in the past, and thus selection of a low voltage threshold for possible load shedding is quite complicated. Hence, LIVES could help ascertaining that the level of system degradation is sufficient to justify an extreme action, such as load shedding.

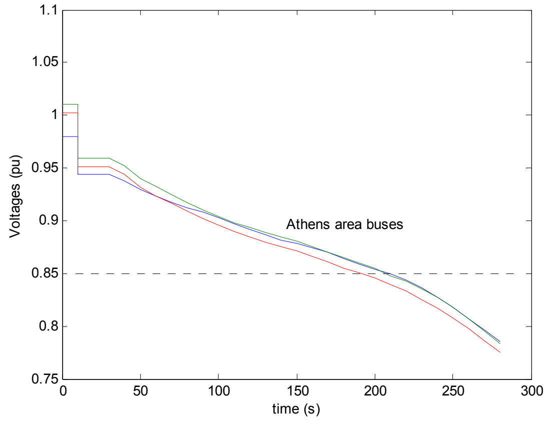


Figure 5: Voltages in Athens area

4.2 Evaluation of load-shedding based on LIVES

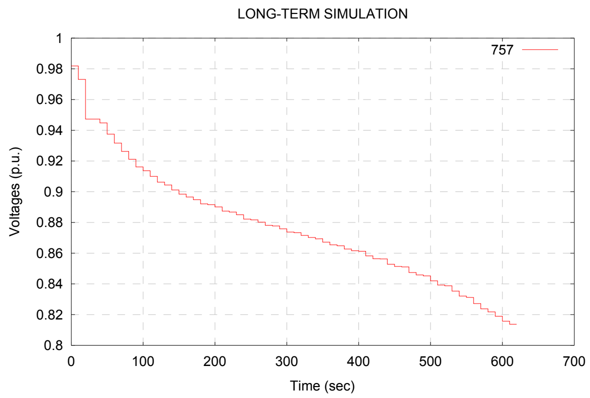
In this subsection we repeat the QSS simulation of the same contingency for July 23, 2007, but this time including the limits on LTC tap range. The effect of LTC limits is that the devices that have exhausted their control range do not enter in the summation of (6). This definitely delays the onset of instability, as well as the emergency detection by the LIVES algorithm. Note also that as long as some LTCs are able to reach their deadband, they too do not participate in the summation of (6), thus the emergency condition monitored by LIVES is even further delayed.

In this simulation, in addition to LTCs and OELs, the effect of armature current limit [8] on generators is also included. As generators located near the load center become overexcitation limited, some of them are forced to reduce active power output to avoid stator overcurrent due to the resulting low terminal voltage.

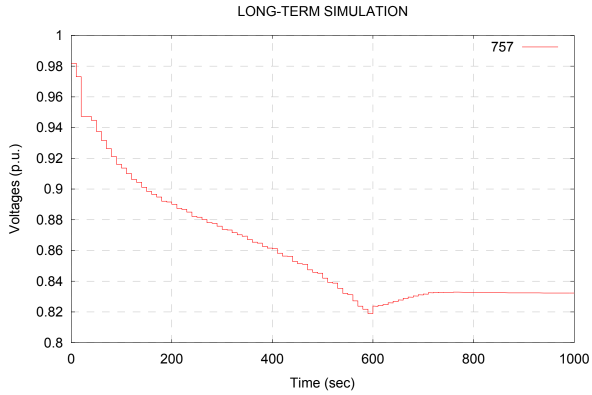
As seen in Fig. 6a and 7a, where the voltages at the transmission (150 kV) buses at Rouf substation in Athens and a substation in Patra are shown respectively, the system in this case is still collapsing but with a much slower pace, so that the final collapse (loss of short-term equilibrium) occurs at simulated time t=620s.

Applying again the LIVES algorithm it is seen that this time, due to the tap limits reached in some important buses in the area of Patra, only the distribution buses in the part of Western Greece connected to Peloponnese issue an alarm 20 seconds before the collapse at time t=600s.

The tap ratio and the distribution side voltage of bus GAETOL51 is shown in Fig.8. As seen distribution side voltage starts decreasing after the tap at t=590s and after the second unsuccessful tap change of t=600s an alarm is issued by the LIVES system.

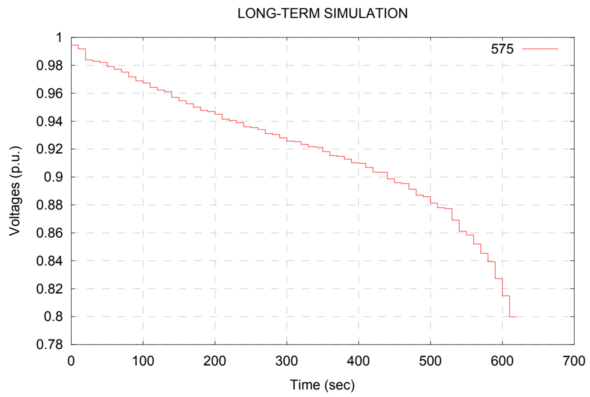


(a)

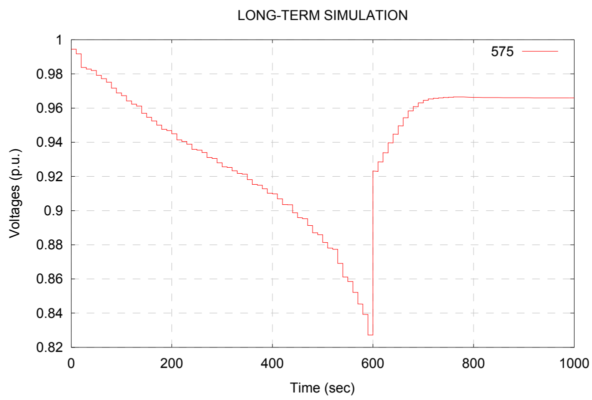


(b)

Figure 6: Voltage at Rouf (without and with load shedding)



(a)



(b)

Figure 7: Voltage at Patra (without and with load shedding)

This simulation shows that due to the combined effect of tap limits and deadbands the LIVES alarm may be signaled in few buses only. Thus we consider in the sequel a protection system, which based on a single alarm would shed 20% of the load at all buses of Table 2, except a few ones representing industrial or agricultural loads, as well as the load on the island of Zakynthos. The amount of load shed on each distribution bus is shown in Table 3. As seen the total load shed in this scheme is less than 100 MW. This amount is considered close to the minimum that can create a significant effect on the system. Thus a smaller amount, or a gradual, more refined shedding is not considered in this paper.

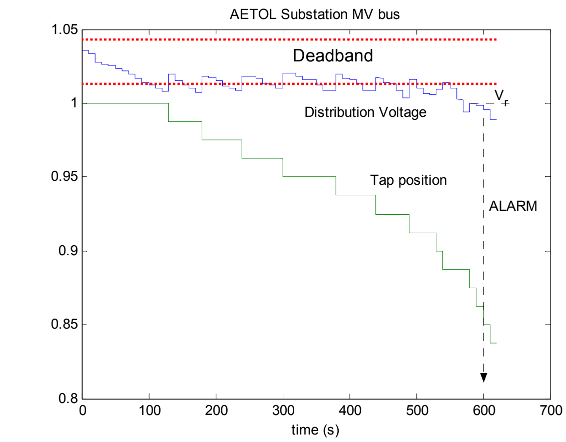


Figure 8: GAETOL S/S distribution voltage and tap position

Bus	ΔP (MW)	ΔQ (MVar)
GTRICH51	-3.77	-2.47
GTRICH52	-3.30	-3.43
GAETOL51	-2.57	-1.61
GAETOL52	-4.97	-1.92
G1PATR51	-5.75	-2.40
G1PATR52	-5.19	-2.90
G2PATR51	-3.07	-1.16
G2PATR52	-3.82	-2.03
G3PATR51	-6.68	0.00
G3PATR52	-6.70	0.00
GVZPAT51	-6.31	0.00
GXILOK51	-2.38	0.00
GXILOK52	-2.31	0.00
GKRANI51	-6.15	0.00
GAMALI51	-3.20	-0.65
GAEGIO51	-5.68	-1.96
GAEGIO52	-3.90	-2.43
GKIPAR51	-2.58	0.00
GKIPAR52	-5.74	-1.09
GPYRGO51	-2.59	0.00
GPYRGO52	-6.36	0.00
Total	**-93.01**	**-24.06**

Table 3: Load shedding per bus

The effect of the proposed load shedding in avoiding the collapse is clear in Figs 6b and 7b. Thus the use of LIVES alarm to shed load locally in the area indicated by the buses in Table 3 is able to prevent an imminent blackout. Voltages in Athens region, which remain still very low after load shedding, can be adjusted at a later stage.

Judging by the amount of load that is sufficient to restore stability, this is a rather marginal instability case. Note that the less severe the instability, the more time it takes for LIVES to identify it. This is not necessarily a disadvantage, as faster action for more severe cases is in general desirable.

5 DISCUSSION AND CONCLUSIONS

This paper reviewed a new method for local identification of voltage emergency that can be used as part of an SPS that will contribute in protecting the Hellenic Interconnected System against the danger of voltage collapse. In particular, the performance of the proposed indicator was evaluated through the simulation of the most dangerous contingency identified during peak load conditions by the on-line VSA operating at the HTSO Control Center.

The simulation of the unstable contingency showed that the proposed LIVES algorithm was able to identify through simple local measurements the area mostly affected by the instability, which includes the part of Western Greece connected to Peloponnese, as well as several buses in western Peloponnese mainly in the wider area of Patra.

The main advantage of the proposed algorithm is definitely its simplicity, since it can be implemented locally at each LTC requiring only readily available measurements. In theory, when all LTCs are acting, the LIVES algorithm can identify an emergency before the stability limit is reached. However, the study performed demonstrated that the alarm could be considerably delayed because of the combined effect of deadbands and LTCs exhausting their tap range. As a result it may be advisable to use some minimal communication, so that, if at least one alarm is issued, load could be shed from several buses in a small area in a coordinated manner.

In any case, it was shown in the paper that a disconnection of less than 100 MW of load in the small area identified through LIVES simulation would be sufficient to avert the voltage collapse caused by the most dangerous contingency considered so far.

Ideally, it would be desirable to install a purely decentralized, closed-loop load-shedding system that would disconnect variable amounts of load in multiple steps, as in [3], using the LIVES alarms to initiate and, if needed, repeat the shedding actions. However, when some LTCs reach their control range limits, LIVES cannot perform a stability test on the corresponding buses. On the other hand, it is likely that these buses are among the most effective for load shedding, as their transmission voltage will be the most depressed. Thus some type of coordination seems to be necessary, always within a predefined relatively small area, for a successful emergency control scheme. A technique to overcome the above problem is proposed in [13].

Clearly, further research is necessary to investigate several implementation issues, such as measurement noise and filtering, as well as the coordination between LIVES and existing or future SPS designs.

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