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Reverse-Logic Control of Load Tap Changers in Emergency Voltage Conditions

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***Abstract*— This papers deals with the emergency control of Load Tap Changers (LTCs) to face low transmission voltages or voltage instability situations. The proposed simple control logic consists in reverting the tap movements once the voltage at a monitored transmission bus falls below some threshold. A deadband on this voltage allows the system to settle down in between the normal and reverse logic modes. In order to control a large number of LTCs, the latter are divided into clusters, each with its own monitored voltage. The paper also considers the control of two levels of LTCs in cascade, where proper coordination is required between the two levels. The proposed scheme has been tested on a detailed EHV-HV-MV planning model of the Western region of the French transmission system operated by RTE. Long-term time responses to major disturbances are shown to illustrate the performance of the proposed scheme.**

***Index Terms*— Long-term dynamics, load tap changers, voltage instability, Emergency control, coordinated voltage control**

I. INTRODUCTION

Load Tap Changers (LTCs) play an important role in long-term voltage instability [1]. Over the last 15 years, several publications have analysed the dynamics of these components [2], [3], [4], [5], [6], [7], [8] and proposed modified control logics [3], [9], [10], [11], [12], [13], [14].

Simply stated, by restoring distribution voltages to their setpoint values, LTCs restore the power of (voltage dependent) loads to their pre-disturbance values. Voltage instability results when the combined generation and transmission system can no longer deliver this power, for instance due to a disturbance [15].

Tap changer blocking is thus often cited as an emergency control action against voltage instability. The drawbacks of this technique are that another load restoration process (e.g. thermostatic loads) may keep on depressing transmission voltages and, when other events occur on the system, the distribution voltages vary with the transmission ones. An alternative consists in moving the tap changers to a predefined position. However, a single position may not suffice to face all scenarios. Finally, a well-known technique consists in decreasing the voltage setpoint of LTCs. Again, this technique cannot counteract other load restoration processes, and raises the problem of choosing the best modified setpoint. In all cases, one must also identify on which LTCs to act.

To the authors' knowledge there has been relatively little attention paid to devising a true emergency control of LTCs, to be used after major disturbances. This paper addresses this issue by proposing a modified LTC control logic in which transmission voltages are preserved once they reach some unacceptably low value. The method is an extension of the one originally proposed in [9], with a more satisfactory handling of several LTC levels.

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II. REVIEW OF INSTABILITY MECHANISM BY LTCS

Consider the system of Fig. 1 where a load is fed by a generator through a (long) transmission line and a transformer with LTC. For simplicity, we assume an ideal transformer (or correct the network and/or load model to account for a real transformer). The load is represented by the exponential model:

$$P = P_o \left(\frac{V_\ell}{V_o}\right)^\alpha = P_o \left(\frac{V}{r\,V_o}\right)^\alpha \quad (1)$$

$$Q = Q_o \left(\frac{V_\ell}{V_o}\right)^\beta = Q_o \left(\frac{V}{r\,V_o}\right)^\beta \quad (2)$$

in which r is the ratio of the ideal transformer, V_ℓ the load voltage and V the network voltage.

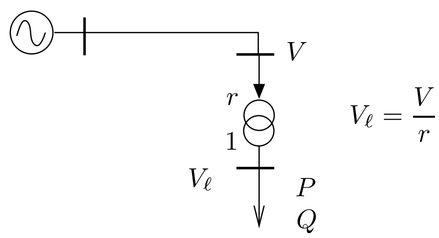

Fig. 1. Illustrative two-bus system

The corresponding PV curves are shown in Fig. 2. All curves refer to the high voltage side of the transformer. The system operating point is O. The dotted line is the *short-term load characteristic*, corresponding to Eqs. (1,2). There is one such curve per value of r. The vertical dashed line is the *long-term load characteristic*. The latter is a constant power since in the long-term the LTC restores the voltage V_ℓ to the setpoint V_o, and hence the load power P to P_o (we assume, again for simplicity, that the reference voltage of the load model is the LTC voltage setpoint). Finally, the curve drawn with solid line is the *network characteristic*, defined as the set of (V,P) points for all possible values of r [15].

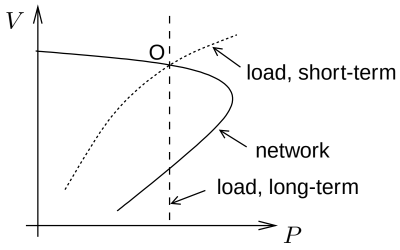

Fig. 2. Load and network characteristics

A typical instability scenario triggered by a large disturbance is sketched in Fig. 3. Under the effect of the disturbance, the network characteristic changes as indicated in the figure. Right after the disturbance, the operating point (short-term equilibrium) is A, where the load power is smaller than P_o and hence the load voltage V_ℓ lower than V_o. Therefore, the LTC attempts to restore this voltage by decreasing r. The dotted lines are the short-term load characteristics corresponding to the successive values of r. The resulting operating points are B, D, etc. Clearly, the LTC attempts to restore the load voltage are hopeless since, for the severe disturbance considered, the post-disturbance network characteristic does no longer cross the long-term load characteristic; long-term equilibrium has been lost. Furthermore, below the *critical point* C, the tap changes have opposite effects: V_ℓ decreases, as indicated by the decrease in load power P.

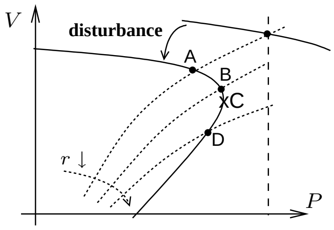

Fig. 3. Large-disturbance instability scenario

In a real system, this degradation may be stopped by LTCs hitting their limits or it can trigger an instability of the short-term dynamics (loss of synchronism, motor stalling [15]).

III. Reverse-logic control of LTCs

A. Principle

Clearly, the long-term instability mechanism outlined above is caused by the "blind" action of the LTC below the critical point. This can be counteracted by changing the LTC control law so that the transmission voltage V is prevented from falling below some threshold V^{min}.

The proposed modified logic is shown graphically in Fig. 4. As long as the transmission voltage V remains above $V^{min}+\delta$ the LTC operates as usual, decreasing r if $V_\ell < V_o - \epsilon$, increasing r if $V_\ell > V_o + \epsilon$, and doing nothing if V_ℓ lies in the deadband $[V_o - \epsilon \;\, V_o + \epsilon]$. On the contrary, as soon as V falls below $V^{min} - \delta$, the LTC increases r in order to decrease the load voltage (and power), and hence increase V. This modified behaviour is referred to as *reverse logic* in

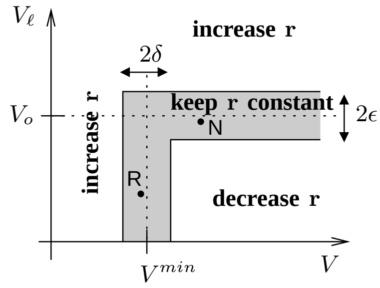

Fig. 4. Modified LTC control logic

the sequel. The deadband $[V^{min} - \delta \;\, V^{min} + \delta]$ prevents from oscillating in between the two logics. Following a disturbance, the final operating point will be either:

- like N in Fig. 4, where the load voltage and power are restored (except for the deadband effect), or
- like R, where load voltage has been decreased to prevent V from falling below V^{min}.

The final operating point will lie in the non-grayed areas of Fig. 4, only if the LTC hits a limit.

Let us emphasize the *closed-loop* nature of the modified control. Once the reserse logic has been activated, and as long as the LTC is not limited, r will be automatically adjusted so as to prevent V from falling below $V^{min} - \delta$. This will occur, for instance, if another load restoration process or an increase in demand is taking place. This behaviour would not be obtained with a mere LTC blocking. Moreover, the closed-loop nature of the control guarantees the robustness of this emergency control scheme with respect to the inevitable uncertainties on the load behaviour.

B. On the choice of V^{min}

Clearly, the choice of V^{min} is a keypoint of the technique. Three situations are sketched in Fig. 5. In all three cases, F is a stable equilibrium point with respect to the LTC long-term dynamics, with trajectories converging towards F under the effect of normal logic on one side and reverse logic on the other side.

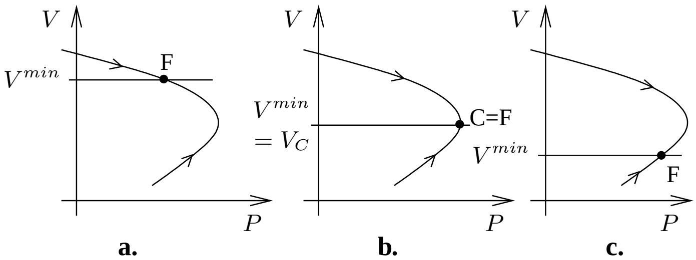

Fig. 5. The three possible choices of V^{min}

From the customer viewpoint, the best situation is the one of Fig. 5.b where the load power and hence the load voltage is maximal. To this purpose V^{min} must be set to the critical point voltage V_C. The latter, however, will most often change from one operating point or one disturbance to another. While the critical point can be easily determined in off-line time simulations (using sensitivity analysis [16], [15]), its on-line identification in post-contingency conditions remains a challenge.

Moreover, in practice, in order to prevent system degradation, for instance the risk of having pieces of equipment tripped by undervoltage or overcurrent protections, it may be required to act before the critical point is reached. This leads to the situation of Fig. 5.a, where transmission voltage is preserved at the expense of a smaller customer voltage. In other words, transmission voltage quality is preferred to customer voltage quality.

The situation of Fig. 5.c is not desirable since, by setting V^{min} to a higher value, better voltages could be achieved at both the transmission and the customer levels.

C. Control of multiple LTCs in a single layer

The above scheme is straightforwardly extended to multiple LTCs connected in a single layer, as shown in Fig. 6.

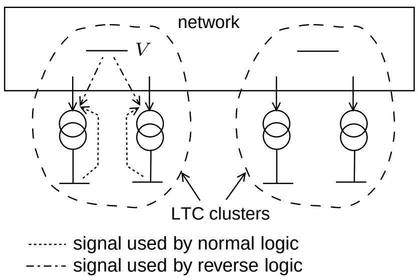

Fig. 6. Multiple LTCs in a single layer

As regards the monitored transmission voltages, one possibility is to have each LTC monitoring the high-voltage side of its transformer. The main drawback, however, is the high number of V^{min} thresholds to adjust.

An alternative, considered in the remaining of this paper, consists in grouping LTCs into "clusters" and monitoring, in each cluster, the voltage V of a single, representative transmission bus to trigger the reverse logic on all LTCs in the cluster (see Fig. 6). Obviously, in normal operating conditions, each LTC controls its own low-voltage bus, as usual. This scheme requires to broadcast the transmission voltage measurement V to the various substations where LTCs are located (in any case, this communication cannot be avoided in the presence of multiple LTC layers, as discussed in the next section).

The clusters and the representative transmission buses can be identified on the basis of electrical distances, or terms of the sensitivity matrix of voltages to transformer ratios.

D. Control of multiple LTCS in several cascaded layers

Many systems have several layers of LTCs in cascade, for instance between EHV transmission, HV subtransmission, and MV distribution, as shown in Fig. 7.

Cascaded LTCs are known to interact and produce oscillatory responses to large disturbances [1], [15]. On the other hand, they provide a larger range of variation of the total ratio available between transmission and distribution levels, and hence offer a potentially stronger reaction against emergency conditions.

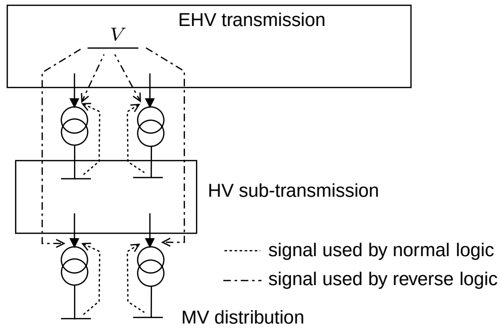

Fig. 7. Multiple LTCs in two cascaded layers

Assuming a structure like in Fig. 7, a cluster is now made up of the EHV-HV transformers feeding the same sub-transmission area together with all HV-MV transformers located downstream. For all LTCs within a cluster, the reverse logic is triggered by the voltage V at a single, representative transmission bus. However, the value of V that triggers the reverse logic will be different from one LTC layer to the other. We denote by V_u^{min} (resp. and V_l^{min}) the threshold used in the upper (resp. lower) layer of a given cluster.

These values have to be carefully chosen. The simulation results reported in Section IV indicate that it is most appropriate to chose $V_u^{min} < V_l^{min}$. With this choice, if the transmission voltage can recover to a value V such that $V_u^{min} < V \leq V_l^{min}$, the upper layer LTCs operate normally and restore HV voltages to their setpoint values, while the lower layer LTCs decrease the MV voltages, and hence the load power, as required to preserve transmission voltages. Now, by restoring HV voltages to their setpoint values, the reactive losses of sub-transmission networks decrease and the capacitive support of HV shunt compensation increases, which decreases the reactive power drawn from the EHV transmission system. This, in turn, allows the load voltages to be eventually somewhat increased. A similar conclusion regarding the control of intermediate voltages was drawn in [11], although in a bit different context.

Note that when a severe disturbance causes V to drop below V_u^{min}, both layers work in reverse logic to preserve the transmission system.

E. Delays

Tap changes are intentionally delayed, to avoid unnecessary reaction to voltage transients. Usually, once the controlled voltage leaves its deadband, the first tap change is more delayed than the subsequent ones. Furthermore, in the presence of several cascaded layers, the higher the layer, the shorter the delay on the first tap change [1], [15].

In emergency conditions, the objective being to quickly stop the system degradation, we propose to make the tapping delay of each transformer as short as possible (taking into account mechanical constraints) as soon as its enters reverse logic, irrespective of the layer and whether it is the first step change or not.

IV. RESULTS

A. Test system

The proposed control logic has been tested on a detailed planning model [16] of the Western part of the French transmission system, operated by RTE. In this region, operating constraints are often linked to voltage instability. A one-line diagram is shown in Fig. 8. The model has 1244 buses, 1090 lines and 541 transformers, and involves:

- the main EHV (380 and 225-kV) grid of France;
- in the Western part of the country: a detailed representation of the HV (90 and 63-kV) subtransmission networks. Eighteen areas are connected to the 225-kV (one to the 380-kV) grid through 90 LTC-controlled transformers, as sketched in Fig. 7. The boundary of these areas are shown with dotted lines in Fig. 8;
- connected to the above areas, 341 LTC-controlled HV-MV transformers feeding MV distribution feeders, to which the (shunt compensated) loads are connected. The latter are modelled as in (1,2).

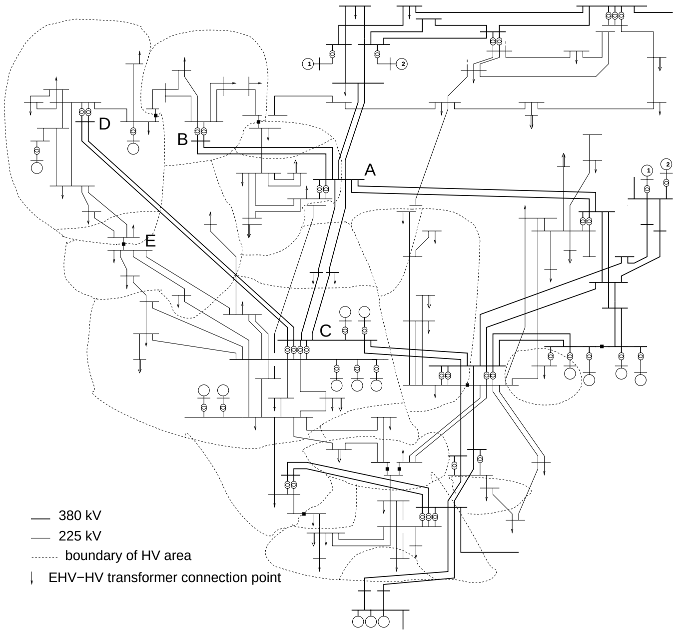

Fig. 8. One-line diagram of the Western region of the RTE system

Quasi Steady-State (QSS) simulation [16], [15] has been used. The dynamics of all LTCs are reproduced, with either the usual or the modified control. In (or close to) the region of interest, 36 generators are modelled with their overexcitation limiters while, farther away, a simpler representation is used. The QSS simulation also accounts for the presence of several secondary voltage regulators. The latter, in operation since 1979 [17], control generator voltages so as to regulate the EHV voltages of "pilot nodes" at setpoint values and share the reactive power generation in accordance with the individual generator capabilities.

B. Reverse-logic settings

The above mentioned 18 HV areas have been used to group LTCs into clusters. Hence, the clusters are identified by the dotted curves in Fig. 8. Each of them includes several EHV-HV transformers (identified by arrows in the figure) as well as all the HV-MV transformers connected downstream (not shown). Within each area, a 225-kV bus has been selected, whose voltage is used to trigger the reverse logic on all LTCs present in the corresponding cluster. For simplicity, the same value of V_u^{min} (resp. V_l^{min}) is used in all clusters, as well as the same deadband $\delta = 0.01$ pu. Obviously, all these choices could be optimized to obtain even better results.

C. Unstable scenario

We consider a severe contingency including the loss, at $t = 10$ s, of the double-circuit line between A and B in Fig. 8.

1) Usual LTC logic: With the usual LTC logic, the system is long-term voltage unstable. This is illustrated in Fig. 9, which relates to an EHV-HV (upper plot) and an HV-MV (lower plot) transformer, both located in the area most affected by the disturbance (close to bus B). All LTCs are oriented as in Fig. 1, i.e. in normal logic they decrease the transformer ratio in order to increase the controlled voltage.

As can be seen, the LTCs cannot restore their voltages. Since they eventually hit their limits, the EHV voltage settles down but at a low, unacceptable value.

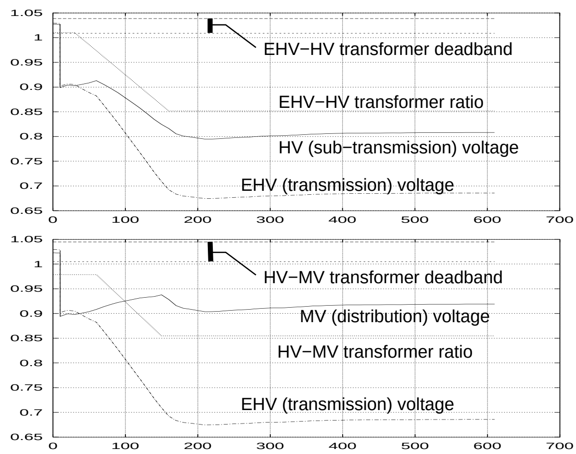

Fig. 9. Usual LTC logic: voltages and transformer ratios (all in pu)

As previously recalled, this long-term instability is characterized by the inability of restoring load powers to their pre-disturbance values. This can be measured by the *unrestored load power* [18]:

$$\Delta P(t) = \sum_{i \in \mathcal{I}} \left[P_i(0^-) - P_i(t) \right] \tag{3}$$

where $P_i(0^-)$ is the pre-contingency active power of the load at bus i, $P_i(t)$ the same load power at time t, and the sum extends over the set $\mathcal{I}$ of LTC-controlled buses, whose voltage is *below* the LTC deadband (i.e. $V_i < V_i^o - \epsilon$). In normal post-contingency conditions, LTCs succeed in restoring their voltages and ΔP comes back to zero. With the load model (1), Eq. (3) takes on the form:

$$\Delta P(t) = \sum_{i \in \mathcal{I}} P_{oi} \left[1 - \left(\frac{V(t)}{V_{oi}} \right)^{\alpha} \right] \tag{4}$$

which shows that ΔP accounts for unrestored customer voltages while taking the load magnitude into account.

The time evolution of ΔP for the above disturbance is shown with solid line in Fig. 10. The final nonzero value confirms the instability. The index passes through a maximum at $t = 100$ s, which corresponds to a behaviour already noted on the 2-bus system. The final increase is due to Secondary Voltage Regulation (SVR) which makes the transmission, and hence the distribution voltages somewhat increase. This is confirmed by the curve drawn with dotted line, which corresponds to the same scenario but without SVR. Because the voltage control range of generators is limited and LTCs act faster than SVR, the latter cannot prevent instability.

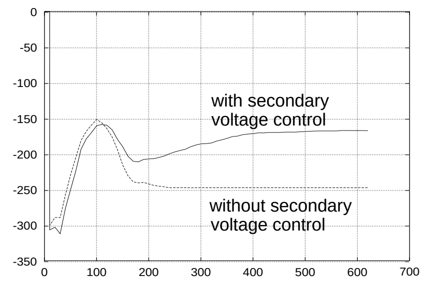

Fig. 10. Usual LTC logic: unrestored load power

2) Modified LTC control: Figure 11 shows the successful operation of the proposed modified control, both in terms of transmission voltage (upper plot, relative to the same bus as in Fig. 9) and unrestored load power (lower plot).

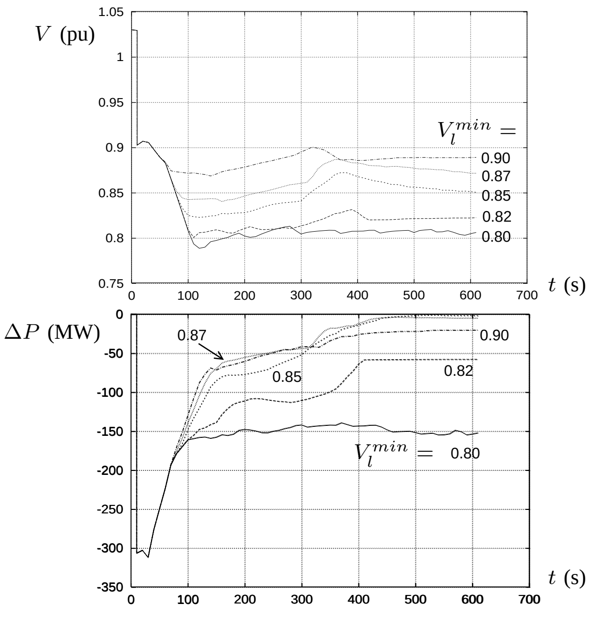

Fig. 11. Modified LTC control with V_u^{min}= 0.82 pu and various values of V_l^{min}: evolution of transmission voltage and unrestored load power

The various curves have been obtained by varying V_l^{min}, with V_u^{min} set to 0.82 pu. As can be seen, for each value of V_l^{min}, the transmission voltage finally settles down in the corresponding $[V_l^{min} - 0.01 \; V_l^{min} + 0.01]$ deadband. As expected, the final value of the unrestored power ΔP depends on the choice of V_l^{min}. It is noteworthy that by setting V_l^{min} to 0.85 or 0.87 pu, only a very small unrestored power is left.

In fact, this excellent behaviour is due to the combined effects of the modified LTC logic and secondary voltage regulation. This can be seen from Fig. 12 which relates to the same scenario, but without SVR. Compared to (Fig. 11), there is more unrestored load power at the end without SVR. When V_l^{min} is set to 0.85, 0.87 or 0.90 pu, the HV-MV LTCs hit their lower limits, and hence transmission voltages cannot be increased up to the requested value.

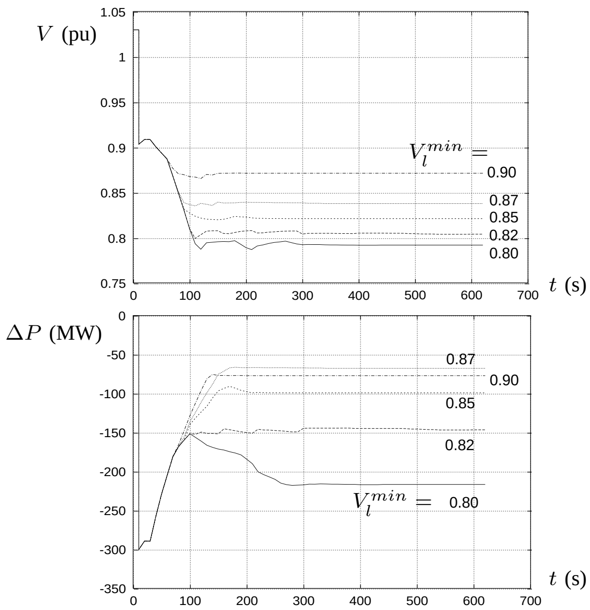

Fig. 12. Same case as in Fig. 11 but without secondary voltage control

The analysis of Figs. 10, 11 and 12 shows that, by stopping the system degradation, the modified LTC control gives SVR time to act and contribute to the improvement of the post-contingency system evolution, with benefits at both transmission and distribution levels. All in all, there is a better coordination of the controls avaiblable to face the emergency conditions.

3) Influence of voltage thresholds: As discussed in Sections III-B and III-D, the voltage thresholds used to trigger the reverse logic have to be properly chosen with respect to the critical point voltage and from one LTC layer to the other.

For the test system under consideration, an investigation of the influence of these thresholds is reported in Table I, which shows the *final* value of the unrestored power ΔP for various combinations of the V_u^{min} and V_l^{min} thresholds.

TABLE I

FINAL VALUE OF ΔP (MW) FOR VARIOUS VALUES OF V_u^{min} AND V_l^{min}

		$V_u^{min} =$ (pu)				
		0.80	0.82	0.85	0.87	0.90
	0.80	-75	-150	-165	-200	-260
	0.82	-30	-60	-160	-190	-260
$V_l^{min} =$	0.85	**-5**	**-5**	-30	-155	-260
(pu)	0.87	**-5**	**-5**	-10	-55	-230
	0.90	-20	-20	-25	-25	-80

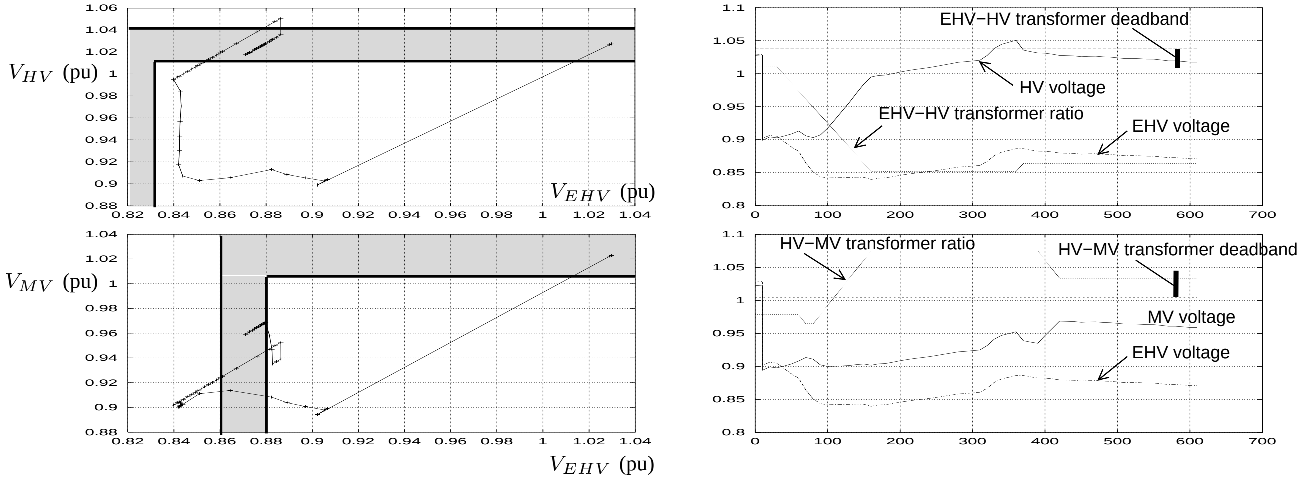

Fig. 13. Modified LTC control, $V_u^{min} = 0.82$, V_l^{min} =0.87 pu

The following conclusions may be drawn: (i) V_u^{min} must be taken smaller than V_l^{min}; (ii) the two values should be a little different; (iii) V_l^{min} should not be set too high otherwise the HV-MV taps will hit their limits and distribution voltages will be less satisfactory.

The first two choices lead to restoring subtransmission voltages to their setpoint values, which yields the benefits explained in Section III-D.

In the above case, the most appropriate settings are those leading to the small final unrestored load powers shown in bold in Table I.

The system behaviour for $V_u^{min} = 0.82$ and $V_l^{min} = 0.87$ pu is illustrated in Fig. 13. The latter relates to the same transformers as Fig. 9, to which the right part of Fig. 13 can be compared. In the left part of the figure, the system "trajectory" is superimposed to diagrams of type shown in Fig. 4, each relative to one of the transformers.

The EHV-HV transformer starts acting at $t = 40$ s (after the initial delay) and since the monitored EHV voltage never falls below $V_u^{min} - \delta = 0.81$ pu, it follows the usual logic until its tap is lower limited at $t = 160$ s. The HV-MV transformer starts acting at $t = 70$ s (after the initial delay), makes one step in normal logic, stops (when the monitored EHV voltage falls below $V_l^{min} + \delta = 0.88$ pu), and switches to reverse logic (once the EHV voltage falls below $V_l^{min} - \delta = 0.86$ pu), until its tap is upper limited, at $t = 160$ s. From there on, the system evolves under the effect of other LTCs and SVR. As the latter succeeds in increasing transmission voltages, the EHV-HV transformer eventually makes a few step back to avoid HV overvoltage, while the HV-MV transformer briefly switches back to normal logic, before settling down in the $V_l^{min} \pm \delta$ deadband.

4) Influence of load parameters: We have mentioned in Section III-A that the closed-loop nature of the proposed modified LTC control compensates for the uncertainties in load behaviour. This property is illustrated in Fig. 14, which shows the system response obtained with the proposed modified logic, for different values of the load exponents α and β in (1, 2). All simulations correspond to $V_l^{min} = 0.85$ and $V_u^{min} = 0.82$ pu, previously identified as one of the best setting combinations (see Table I). The values $\alpha = 1.4, \beta = 2$ have been used in all other simulations of this paper.

As expected, the smaller the value of α and/or β, the larger the initial drop in transmission voltage and load power.

As can be seen, in all cases, the modified LTC control succeeds in maintaining the final transmission voltage close to V_l^{min} and restoring most of the load power, in spite of the wide variation assumed for the exponents. The oscillatory behaviour observed in some cases is probably due to an interaction between SVR and LTCs.

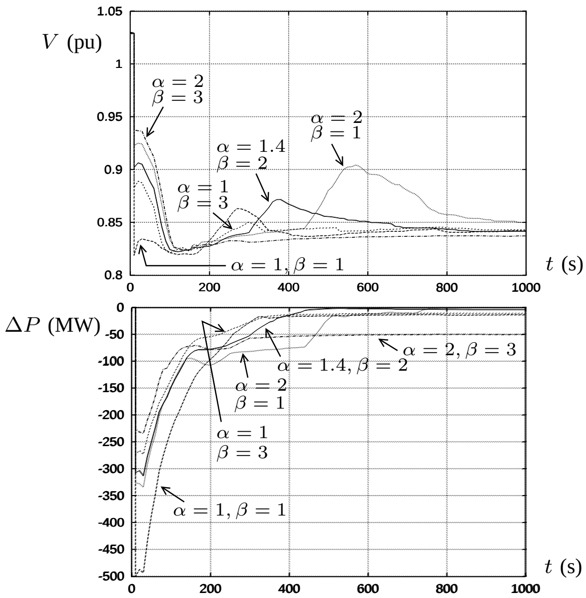

Fig. 14. Modified LTC control: system response for various load models

D. Stable but low-voltage scenario

Finally, we present the results obtained with another disturbance, namely the tripping of the double-circuit line between buses C and D, with the busbar breaker E closed (see Fig. 8;

this allows the power to reach the Western end of the system through the 225-kV network).

Figure 15 shows the time evolution of a transmission voltage in the most affected area and the unrestored load power at the system level.

The curves drawn with solid line relate to the usual LTC control. As can be seen, the system is not unstable but experiences a deep, unacceptable voltage drop, which is attributable to the cascaded LTCs.

The other curves show the performance of the proposed modified logic, for various values of V_l^{min}, V_u^{min} being set to 0.82 pu. Here, the criterion for chosing V_l^{min} is no longer the final value of ΔP (which is zero in all cases, as for the normal LTC control) but rather the time for the transmission voltage to reach its final value. In this respect, the best setting is $V_l^{min} = 0.90$ pu, which leads to a very smooth post-disturbance evolution.

However, as a common setting has to be taken for all possible contingencies, $V_l^{min} = 0.87$ pu seems to be a good compromize between this scenario and the previous one. As already mentioned, no attempt has been made to optimize V_l^{min} in each area, in which case a better compromize could be found.

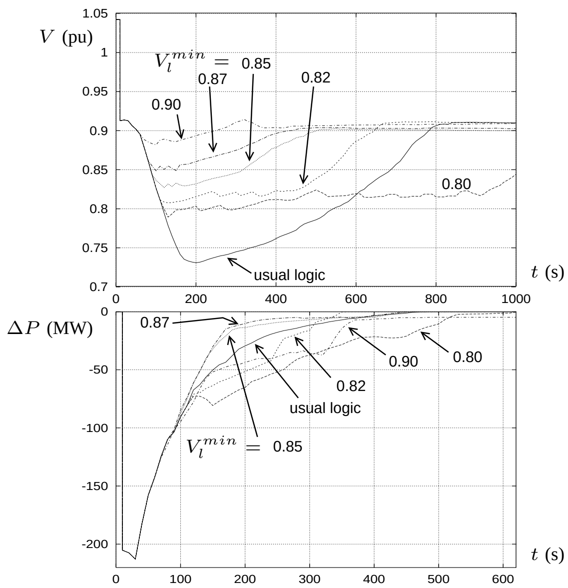

Fig. 15. Usual and modified LTC control, with V_u^{min}= 0.82 pu and various values of V_l^{min}: evolution of transmission voltage and unrestored load power

V. Conclusion

This paper has proposed a modified LTC control logic, for use in emergency (low or unstable) voltage conditions. Simply stated, the principle is to reverse the tap actions once the transmission voltages fall below some threshold. A deadband stabilizes the system in between the normal and the reverse logics. This modified control is applied to clusters of LTCs, each of them relying on the voltage measured at a representative transmission bus.

The scheme operates in closed-loop in the sense that, once the reverse logic is activated, the transmission voltage is kept close to the threshold value. This property guarantees the robustness of the modified control against load behaviour uncertainties.

The paper has also discussed the choice of the above mentioned threshold, with proper consideration for cascaded LTC structures.

The main limitation of the method is the limited range of variation of the transformer ratios while its cost is linked to the transmission of grid voltage measurements to the substations where LTCs are located and, obviously, the modification of the local LTC controllers.

The method has been extensively tested on a realistic EHV-HV-MV model of the Western part of the French system, where the proposed logic has been found to work very satisfactorily.

Among the future extensions, let us quote the definition of LTC clusters, the choice of the representative transmission buses and the optimization of the voltage thresholds within each cluster, for a wide range of contingencies.

References

[1] C. W. Taylor, Power System Voltage Stability, McGraw Hill, EPRI Power System Engineering series, 1994

[2] M.S. Calovic, “Modeling and analysis of under-load tap changing transformer control systems”, IEEE Transactions on Power Apparatus and Systems, Vol. 103, pp. 1909-1915, 1984

[3] J. Medanic, M. Ilic-Spong, J. Christensen, “Discrete models of slow voltage dynamics for under load tap-changing transformer coordination”, IEEE Transaction on Power Systems, Vol. PWRS-2, No.4, Nov. 1987

[4] I.A. Hiskens, D.J. Hill, “Dynamic interaction between tapping transformers”, Proc. 11th PSCC conference, pp. 1027-1034, Avignon, 1993

[5] H. Ohtsuki, A. Yokoyama, Y. Sekine, “Reverse action of on-load tap changer in association with voltage collapse”, IEEE Trans. on Power Systems, Vol. 6, No 1, pp. 300-306, 1991

[6] N. Yorino, F.D. Galiana, “Voltage instability in a power system with single OLTC”, Proc. ISCAS ’92 Symposium, Vol. 5, pp. 2533-2536, 1992

[7] C.-C. Liu, K.T. Vu, “Analysis of tap-changer dynamics and construction of voltage stability regions”, IEEE Trans. on Circuits and Systems, Vol. 36, No 4, pp. 575 -590, 1989

[8] K.T. Vu, C.-C. Liu, “Shrinking stability regions and voltage collapse in power systems”, IEEE Trans. on Circuits and Systems- I, Vol. 39, pp. 271-289, 1992

[9] T. Van Cutsem, “Analysis of emergency voltage situations”, Proc. 11th PSCC Conference, Avignon, 1993, pp. 323-330

[10] M. Larsson, D. Karlsson, “Coordinated Control of Cascaded Tap Changers in a Radial Distribution Network”, Proc. IEEE/KTH 1995 Stockholm Power Tech conference

[11] F. Carbone, G. Castelano, G. Moreschini, “Coordination and Control of Tap Changers Under Load at Different Voltage Level Transformers”, Proc. Melecon ’96 conference, Bari

[12] M. Larsson, “Coordinated voltage control in Electric power systems”, Ph.D. dissertation, Lund University (Sweden), 2000

[13] C.D. Vournas, G.A. Manos, “Emergency tap-blocking to prevent voltage collapse”, Proc. of the 2001 IEEE Porto Power Tech conference, Vol. 2

[14] C.D. Vournas, “On the role of LTCs in emergency and preventive voltage stability control”, Proc. of the 2002 IEEE PES Winter Meeting, Vol. 2, pp. 854-859

[15] T. Van Cutsem, C. Vournas, Voltage Stability of Electric Power Systems, Boston, Kluwer Academic Publishers, 1998

[16] T. Van Cutsem, Y. Jacquemart, J.-N. Marquet, P. Pruvot, “A comprehensive analysis of mid-term voltage stability”, IEEE Trans. on Power Systems, vol. 10, 1995, pp. 1173-1182

[17] J.-P. Paul, J.-Y. Leost, J.-M. Tesseron, “Survey of the Secondary Volatge Control in France : Present realization and investigations”, IEEE Transactions on Power Systems, Vol. 2, No 2, pp. 505-511, 1987

[18] T. Van Cutsem, C. Moisse, R. Mailhot, “Determination of secure operating limits with respect to voltage collapse”, IEEE Trans. on Power Systems, vol. 14, 1999, pp. 327-335