On the role of LTCs in Emergency and Preventive Voltage Stability Control

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Abstract: This paper discusses the effect of Load Tap Changers on the Voltage Stability of a power system and in particular under emergency conditions. This discussion covers LTCs both on the bulk power delivery transformers, which are normally controlled automatically, and the transformers between higher voltage levels, typically EHV/HV autotransformers, that in many cases are controlled manually. An algorithm to determine taps for the latter that will maximize loadability is presented.

Keywords: Voltage stability, loadability limits, optimization, Load Tap Changers, emergency and preventive control.

I. Introduction

A typical voltage collapse scenario [1, 2] consists of a period of relatively slow voltage decline followed by an abrupt voltage drop causing usually a blackout after a succession of events, such as loss of synchronism and/or undervoltage tripping of generators.

In other voltage instability scenarios the voltage collapse is avoided and the system settles down at a more or less unacceptable level of transmission voltage, still remaining in operation. This allows a relatively easier restoration of a normal state.

In the second case, the load restoration mechanism driving the voltage instability has reached a physical limit, thus providing a pseudo stabilization allowing the system to settle down. As we will see in the next section, one such mechanism of load restoration is the LTCs of bulk power delivery transformers.

Voltage stability emergency control is primarily concerned with the problem of stopping the evolution of an unstable scenario before its conclusion towards a voltage collapse. In this sense, timing is a critical aspect: time to identify the instability and time to apply the emergency control is essential. For this reason many emergency control measures, such as undervoltage load shedding are based on extensive off-line computations.

Secondly, emergency voltage control aims at providing an acceptable stable operating point of the power system. If the system has avoided voltage collapse, there is usually more time available for restoring a stable operating point, allowing for instance the start-up of back-up generators.

A variety of measures for emergency voltage stability control is available. They include reactive device switching, generation rescheduling, tap changer control, and finally load shedding.

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Faster forms of voltage instability and collapse (usually termed as *short term* voltage instability) have to be counteracted with equally fast devices, such as SVCs and other FACTS devices [1], as well as fast energy storage manipulation. Short-term voltage stability is mainly affected by fast load components such as induction motor load, HVDC links etc. For the slower forms of voltage instability (called *long-term* voltage instability) [2] there is usually enough time for conventional controls to be activated, provided that they have been carefully designed and tuned in advance.

II. Bulk Power Delivery LTCs

Bulk power delivery LTCs form one of the prime mechanisms of voltage instability: by restoring distribution side voltage after a contingency, they also indirectly restore load power of the voltage sensitive loads.

In [3] this property is questioned. Indeed, if the load behind the LTC is modeled as constant power consumption, LTC operation will be beneficial for voltage stability, since by restoring the load voltage, the active and reactive losses on the distribution line are reduced. Moreover, if reactive compensation on the distribution side is represented as constant admittance, its effect is also increased through voltage restoration. These modeling assumptions, however, are not appropriate for actual system representation. Constant power load can be used only on the primary side of LTCs, thus anticipating load restoration [4].

All practical feeders will serve (at least partly) components of voltage sensitive load, such as heating and lighting loads. Thus, by changing the tap in favor of the distribution side voltage, the effective load admittance increases, so that eventually it can become larger than that of the equivalent network feeding the load bus. After this point the process of load restoration becomes unstable, as successive tap changes decrease distribution voltage further and further away from its setpoint. A voltage instability detection relay has been proposed based on the comparison of system and load admittance [5].

Thus, LTCs will in general contribute to voltage instability. There are, however, exceptions to this rule, such as a feeder serving almost exclusively heavily loaded induction motors.

The induction motor is an almost constant active power load, whereas its reactive consumption is dependent on supply voltage. Lightly loaded, uncompensated induction motors demonstrate a positive slope of reactive power consumption with respect to voltage [2, 6]. This is due to the effect of the magnetizing reactance. Heavily loaded, compensated induction motors demonstrate a *negative* slope of reactive power to voltage. In such a case increase of distribution side voltage will decrease reactive consumption and thus it will result in increasing the transmission side voltage as well. For these exceptional feeders fast control of LTCs is beneficial for voltage stability.

Such exceptional feeders are likely in agricultural areas with mainly irrigation (pumping) loads. Another variant is feeders connecting wind parks equipped with uncontrolled induction generators. Apart from these notable exceptions all usual LTCs will contribute to load restoration and can thus become unstable under severe loading conditions.

Therefore, emergency controls on bulk power delivery LTCs is an essential means for stopping the decline to voltage collapse and can be of three types:
1. *Tap blocking*: is the easiest way of stopping an ongoing voltage instability. It is initiated either locally, by monitoring transmission side undervoltage, or remotely by receiving a tap-blocking signal from a control center. In both cases the automatic control of distribution side voltage is blocked and thus the system degradation procedure is terminated.
2. *Setpoint reduction*: is used in certain utilities and is providing a controlled reduction of distribution side voltage.
3. *Tap reversing*: refers to changing the controlled bus from the distribution to the transmission side. In this sense, the LTC is now trying to help the transmission system recovery, using the voltage sensitive load as a means. Note that, when the normal LTC operation has become unstable, reduction of the load admittance will increase both distribution and transmission voltage.

In [7] LTC setpoint reduction is used to stabilize an unstable contingency. Quantification of setpoint reduction in terms of P and Q allows the determination of LTCs where setpoint reduction is more effective, as well as those cases where this will not provide a load reduction at all (as with the exceptional feeders discussed above).

Undervoltage tap blocking [1, 8, 9] is fairly easily applied, but determining the triggering voltage to avoid unnecessary blocking, providing at the same time stabilization of all unstable cases is a challenging task.

In [10] an algorithm to select potentially harmful LTCs was introduced and applied to the Hellenic Interconnected System. Fig. 1 shows the voltage of all primary LTC buses in the system arranged geographically and indicates with a circle LTCs, the blocking of which is sufficient to guarantee stabilization of an unstable point. The results demonstrate that it is very difficult to assess which taps should be blocked based only on geographic location and voltage measurement.

Note that all applications of LTC emergency controls is based on the assumption of voltage sensitive load. Furthermore, quantification of the obtained load reduction is based on load modeling. Thus, incorrect or inexact load modeling will compromise the accuracy of the obtained results.

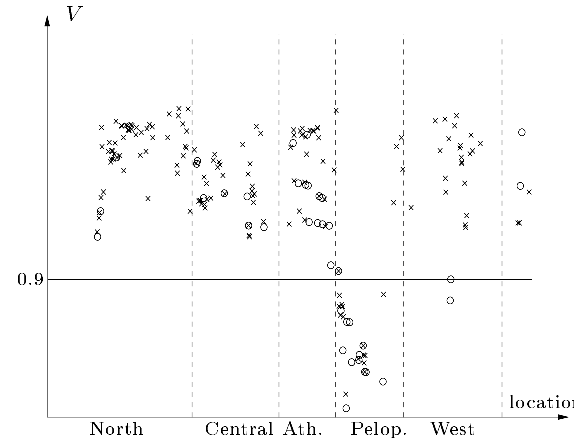

Figure 1: *Voltage on LTC primaries: "o" indicates potentially harmful LTCs*

Another concern is that secondary load restoration processes, such as distribution system voltage regulation, or thermostatic effects [1, 2], may cancel the benefit achieved by LTC emergency control.

As a general conclusion, LTC emergency controls are a softer means of load reduction than firm load shedding, but can be relied upon only temporarily to stop or delay the voltage degradation towards a collapse.

III. Transmission Network LTCs

Load tap Changers are used also at higher voltage levels in autotransformers between high voltage (HV) and extra high voltage (EHV) transmission and subtransmission subsystems.

In the case of a radial system with cascaded levels of LTCs (e.g. EHV/HV, HV/MV) it is easily shown [2] that by boosting the HV side of the upper level (EHV/HV) transformer, the maximum power that can be transferred to the load is increased. This is due to the fact that the reactive losses in the HV network are reduced for increased voltage. The same is also true for generator step-up transformer taps. The practical limitation to this process is obviously the maximum allowable voltage in the HV network.

In [2] it is further shown that automatic control of HV system voltage results in splitting the electrical distance between generation and load into two subsystems separated by the (almost) constant voltage of the HV side. Splitting of the electrical distance obviously increases the maximum power transfer to the load.

A first conclusion drawn is that, if the upper LTC level is controlled automatically, this should be done with a shorter time delay than that chosen for the lower level [1]. Thus the bulk power delivery LTCs will operate only when the network LTCs are unable to restore voltage.

Even though automatic control of transmission network LTCs is beneficial for voltage stability and contributes to increased loadability margins, several technical constraints render this automatic operation problematic in many cases [1]. One obvious reason that makes utilities reluctant to put transmission level LTCs under automatic control, is the reliability of the autotransformers, which are extremely critical for the integrity of the whole network.

Thus, in many power systems the LTCs of EHV/HV autotransformers are operated manually during the daily load cycle, usually according to an OPF output, or other operational criteria.

For power systems that experience voltage stability problems a second-best alternative to automatic control of LTCs is that of assigning tap settings as part of an on-line Voltage Security Assessment (VSA) program. This feature is part of an ongoing European research project titled OMASES (Open Market Access and Security Assessment System). The project consortium is headed by ALSTOM, and the VSA module is developed jointly by NTUA and the University of Liège. The OMASES system will be installed in the Greek EMS run by the Hellenic Transmission System Operator, as well as in the Italian Control Center of CESI. The utilities involved requested that the modification of EHV/HV autotransformer taps should be included among the measures proposed by the VSA module in order to increase voltage security.

Tap modifications of non-automatic LTCs are not affecting customer service (same is true for instance for generator rescheduling) and have the added advantage that they do not interfere with the energy market operation. These tap modifications will be employed only at times where the available security margin is considered unacceptable.

The direction of tap adjustment for increasing the loadability margin depends upon the power transfer pattern. Thus, in certain cases the EHV side voltage and in others the HV system voltage should be boosted. This is due to the fact that with these tap changes the reactive power reserve is redistributed among the generators of the system. In this sense this type of control acts similarly to Secondary Voltage Regulation (SVR), the difference being that SVR acts on generator setpoints directly and during normal operation, i.e. irrespective of the available security margin.

The effect of changes in tap on the loadability margin of a power system can be calculated directly by deriving the loadability margin sensitivities.

Sensitivities of loadability margin to the taps are calculated straight forward based on the work originally presented in [11]. The sensitivity formula, as given in [2] is:

$$\mathbf{S}_{\mu\mathbf{n}} = -\frac{\mathbf{f}_\mathbf{n}^T \mathbf{w}}{\mathbf{w}^T \mathbf{f}_\mathbf{p} \mathbf{d}} \quad (1)$$

where $\mathbf{S}_{\mu\mathbf{n}}$ is the vector of sensitivities of the loadability margin μ with respect to the manually controlled LTC taps $\mathbf{n}$, $\mathbf{d}$ is the direction of stress,

$$\mathbf{f}(\mathbf{x}, \mathbf{p}, \mathbf{n}) = \mathbf{0} \quad (2)$$

is the set of equilibrium equations, $\mathbf{p}$ is the vector of load parameters and $\mathbf{w}$ is the singular vector satisfying:

$$\mathbf{w}^T \mathbf{f}_\mathbf{x} = \mathbf{0} \quad (3)$$

Note that as analyzed in [12], the Jacobian matrix of equilibrium conditions $\mathbf{f}_\mathbf{x}$ will be rectangular, when the loadability limit is not due to a Saddle Node Bifurcation (zero eigenvalue), but to generator switching under overexcitation control.

IV. Demonstrative Example

Consider the system in Fig. 2 with the data given in Table 1. Generators at buses 1 and 2 are of the same size and have limited reactive reserves modeled using their maximum allowable rotor current [2]. We can also think of the two generators as equivalent models of two exporting areas, whereas the load on bus 3 can represent a third area, which is importing power.

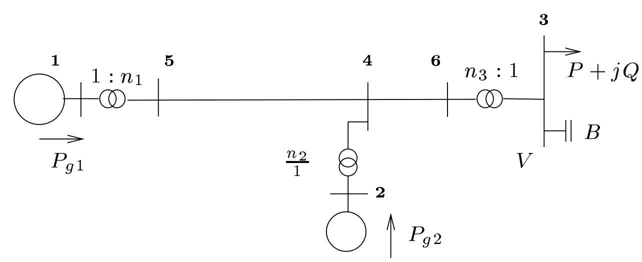

Figure 2: *Test system*

Table 1: *Three LTC system data (pu on common base)*

$X_{15} = X_{24}$	X_{46}	X_{45}	X_{36}
0.032	0.005625	0.068	0.016
$X_d = X_q$	$V_{1o} = V_{2o}$	E_f^{lim}	K_{avr}
0.8	1.0	2.5968	100
$n_{1o} = n_{2o}$	n_{3o}	B	Q
1.04	1.0	0.25	$0.5P$

The three areas are connected through the EHV lines 4-5 and 4-6 and three non-automatic LTC transformers with taps n_i. Bus 3 should be considered as the HV primary of a bulk power delivery LTC transformer, which restores the secondary voltage, and thus the load to constant power P, Q. Shunt compensation B is considered to be on the HV side.

In Fig. 3 the loadability limit on P is plotted as a function of the generation P_{g2} (considered fixed) and for the initial tap settings of Table 1. The load increase is satisfied through an increase of area 1 generation. The loadability limit thus plotted corresponds to the transfer capability from area 1 to area 3.

The loadability limit surface of Fig. 3 consists of two branches $\mathcal{L}_1$ and $\mathcal{L}_2$, both of which are due to generator

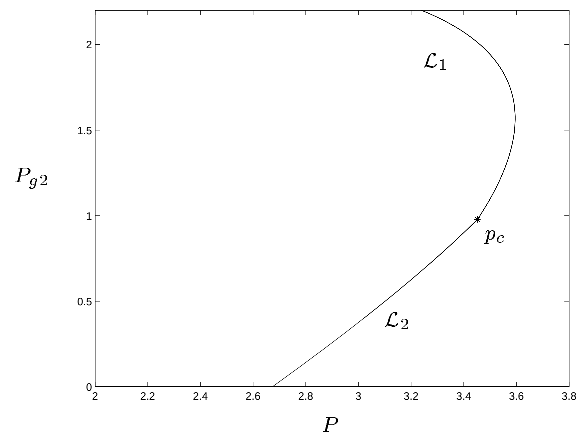

Figure 3: *Loadability limits*

switching from voltage control to constant excitation. At all points on the loadability surface both equivalent generators have reached their maximum excitation limits. However, the order in which they reach the limit changes: in the upper part of Fig. 3 (above the corner point p_c) generator 2 is the first to reach its excitation limit and the loadability limit is met when generator 1 in turn exhausts its reactive reserve. The opposite order of limits is encountered on the lower part of Fig. 3 (below point p_c). For the value of P_{g2} corresponding to the corner point p_c, the two generators reach their reactive limits simultaneously, i.e. for the same value of the load.

Figure 3 shows that generator rescheduling is a very efficient way of increasing loadability margins for this system. However, in this paper we consider the generator pattern fixed and we concentrate on maximizing the loadability margin through LTC tap adjustments.

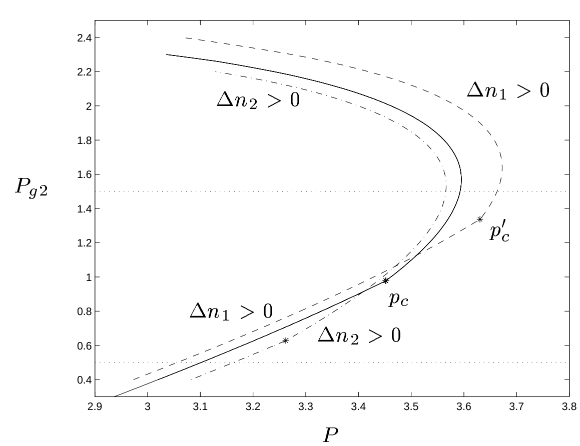

Figure 4: *Variation of loadability limits with taps*

Figure 4 shows graphically how the loadability limits change when the taps n_1 and n_2 are varied. For the upper part of the loadability surface $\mathcal{L}_1$, the loading margin increases with n_1 and *decreases* with n_2. The opposite is true for the lower part $\mathcal{L}_2$. In other words, tapping in favor of EHV is beneficial when the HV system (in this case the equivalent generator) is able to regulate its voltage. On the contrary, increasing the EHV tap when the area feeding the network has reached reactive reserve limits, will not increase in general the EHV side voltage. This is due to the increased consumption of reactive power to transfer P_{g2} to the EHV system.

This property is clarified by considering the changes in EHV system voltage when the taps n_1 and n_2 are varied. In Table 2 the effect of tap changing on voltages, when the system is on the loadability limit, is shown for two values of P_{g2}. As the system is on the limit, only one direction of tap change for each LTC will be inside the feasibility region(see Fig. 4). As seen in the Table, when decreasing the tap corresponding to the limited generator (i.e. the system that has exhausted its reactive reserves) all voltages go up.

Table 2: *Voltage sensitivity to tap changes*

P_{g2}=1.5 pu, P_{lim}=3.593 pu				
Δn_1	ΔV_1	ΔV_2	ΔV_5	ΔV_6
+0.01	+0.000	+0.017	+0.013	+0.019
Δn_2	ΔV_1	ΔV_2	ΔV_5	ΔV_6
-0.01	+0.000	+0.012	+0.001	+0.003
P_{g2}=0.5 pu, P_{lim}=3.102 pu				
Δn_1	ΔV_1	ΔV_2	ΔV_5	ΔV_6
-0.01	+0.022	+0.001	+0.011	+0.005
Δn_2	ΔV_1	ΔV_2	ΔV_5	ΔV_6
+0.01	+0.024	+0.001	+0.023	+0.016

V. Optimal Taps for Maximizing Loadability

Table 3 contains the sensitivities of loadability margin (calculated as outlined in Section III) for the loadability limits with initial taps and for the two values of P_{g2} discussed above. For simplicity we denote these sensitivities as S_i (for tap n_i).

Table 3: *Loadability margin sensitivities to taps*

P_{g2}	branch	S_1	S_2	S_3
1.5 pu	$\mathcal{L}_1$	2.47	-0.89	-0.78
0.5 pu	$\mathcal{L}_2$	-1.51	2.06	-0.23

Note, that the sensitivity to n_3 is always negative, that is loadability is increased by tapping in favor of the HV side, when the transformer is connected to a load area.

Of course, in a more complex system each area will consist of loads, regulating generators and limited generators. The properties, however, shown in this simple example were also encountered in the Hellenic interconnected system of the late '90s [13], where an increase of loadability in the North-South direction was achieved (among other measures) by changing the EHV/HV taps in favor of the Athens load region in the South and in favor of the EHV transmission system in the North, where the main generation is located.

Note that the type of loadability limit encountered may change, as the LTC taps are varied. Consider, for instance, a loadability limit obtained for constant P_{g2} on the upper loadability branch of Fig. 4. By increasing tap n_1 a larger loadability margin is obtained, but at the same time the corner point p_c moves upward to point p'_c. It is thus clear that by changing tap n_1 in this direction the limiting loadability branch will eventually become $\mathcal{L}_2$, for which the tap sensitivity has opposite sign. If taps were continuous variables, it could have been possible to manipulate taps so as to bring the corner point p_c exactly on a constant P_{g2} value. This would correspond to an equal sharing of reactive reserves between the supporting areas 1 and 2, as in Secondary Voltage Regulation, with the result that both are exhausted simultaneously.

The loadability limit at point p_c is characterized by the simultaneous switching of both generators from voltage regulation to constant excitation. The loadability margin sensitivity for this type of limit is obviously different from that of either $\mathcal{L}_1$, or $\mathcal{L}_2$. However, a direction for increasing the loadability margin can be computed by considering the sensitivities for the two loadability margins, adding the constraint that they are both increased by the same amount. Expressed mathematically:

$$\Delta\mu_1 = \sum_{i=1}^{3} S_i^1 \Delta n_i = \Delta\mu_2 = \sum_{i=1}^{3} S_i^2 \Delta n_i \tag{4}$$

where S_i^j is the sensitivity of the loadability margin μ_j (corresponding to branch $\mathcal{L}_j$) with respect to tap n_i.

This results in the optimization technique known as the *gradient projection* method [14]. The algorithm suggested for the determination of optimal LTC settings that maximize the loadability margin for a specific active power pattern (constant P_{g2} in this case) consists of the following steps:

1. Compute the loadability margin for the given active power and load increase (stress) pattern.
2. If the margin is considered insufficient, modify LTC taps along the discretized direction indicated by the sensitivities of the loadability margin encountered (gradient, or steepest ascent method). Calculate the new margin.
3. If the loadability margin is increased, continue as in step 2.
4. If the margin is reduced, calculate the sensitivities of the new margin and return the taps to their previous values. Using the sensitivities of both the new and the old margin determine the direction of tap modification (gradient projection method) and recompute the loadability margin.
5. The optimization process continues until an optimum is found, or all taps reach their limits, or the voltages of the base case with the taps suggested by the optimization step exceed their maximum or minimum permissible values.

Table 4: *Optimization process for tap determination*

iter	n_1	n_2	n_3	P_{max}
0	1.04	1.04	1.00	3.59
1	1.05	1.03	0.99	3.63
2	1.06	1.02	0.98	3.672
3	1.07	1.01	0.97	3.669
New direction for optimization				
	0.50	0.65	-0.64	
4	1.07	1.03	0.97	3.69
5	1.08	1.04	0.96	3.71
6	1.09	1.05	0.95	3.73

Application of this method to the test system for $P_{g2} = 1.5$ pu gave the results shown in Table 4. As seen in this Table, the first three iterations are made along the direction indicated by the sensitivities of Table 3, i.e. by increasing n_1 and decreasing both n_2 and n_3. At the third iteration along this direction the loadability limit decreases. This is because a new loadability branch ($\mathcal{L}_2$) is encountered, with opposite sign sensitivities for n_1 and n_2. Using the sensitivities for both loadability limits the new direction of optimization shown in Table 4 is computed. Thus, from iteration 4 onwards both taps n_1 and n_2 are increased, while n_3 continues to decrease. After iteration 6 the optimization stops, because the voltage at the load bus 3 reaches its upper limit (1.10 pu) at the base case.

Note that during the optimization tap n_2 is varied in two directions, first down and then up. This cannot be avoided, as long as only linearized information is used at each step of the optimization. However, this is only part of the computation process for providing the optimal settings. The actual tap will not be modified before an optimum has been found.

The loadability increase obtained using tap optimization is relatively small in this case (0.14 pu). Thus it appears that tap modification by itself should be used only for minor security limit violations. For more serious security problems tap adjustments should be combined with generation rescheduling. Another associated aspect is that of shunt compensation switching.

VI. LTCs vs. Capacitor Voltage Control

As seen in the previous section, the loadability increase achieved by manual tap rearrangement was limited by an overvoltage limitation for the base loading condition. This would not be the case, if voltages were controlled by switching capacitors. This is a new aspect that is partly beyond the scope of emergency (or preventive) voltage control, however it is worth mentioning as it opens a new perspective.

Shunt capacitive compensation affects the loadability limit pattern by increasing the loadability margin and at the same time redistributing the reactive power among generators. Capacitor banks control can be used in conjunction with EHV/HV autotransformer tap control as in BPA [1]. Other utilities use reactors to compensate long EHV transmission lines, the switching of which greatly increases loadability margins during emergencies [15]. In all cases, shunt reactive device switching is preferable to LTC tap control, as in such a case the voltage is regulated by injection of reactive power (through connection or disconnection of new devices), whereas with LTCs the same effect is achieved by varying load (and network) admittance.

This property can be exploited also in the distribution system [1]. By relying for voltage control on switched capacitor banks voltage instability is not avoided, but the loadability limit is increased. Also, it can be shown that capacitor switching can still regulate voltage, even when the load restoration process through admittance adaptation has become unstable.

In the case where both reactive power devices and LTCs are used to control voltage the former should be switched faster so that the LTCs are the last to act.

The advantages of switched capacitor control over traditional tap changing should be carefully considered when redesigning AC power networks to meet the open challenges of the future: deregulation, restructuring, distributing generation, etc.

VII. Conclusions

In this paper the role of automatic and nonautomatic LTCs for emergency and preventive voltage stability control was reviewed. It was discussed how tap blocking of bulk power delivery transformers LTCs can prevent an approaching voltage collapse, as well as the problems and limitations of this countermeasure.

It was also shown that LTCs at higher voltage levels (including those of generator step-up transformers, if available) can help maximize the loadability margin either by automatic control, or by selection of tap adjustments using off-line optimization.

Some rules for optimizing LTCs at the transmission network level were obtained using a simplified network:

1. Taps should be adjusted in favor of the transmission system for transformers injecting active power from areas with remaining reactive reserves.
2. Taps should be lowered at the transmission system side for transformers injecting active power from areas which have exhausted their reactive reserves.
3. Taps should be adjusted in favor of the load side for transformers feeding areas importing active power through the transmission system.

Finally the voltage control through capacitor switching as an alternative to LTC control was discussed.

Acknowledgement

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Biography

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