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COMBINED CONTROL ACTIONS TO COUNTERACT LONG-TERM VOLTAGE INSTABILITY

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The overexcitation limitation of key generation units is an important factor leading to long-term voltage instabilityand system collapse. The authors investigate control actions that can be used in order to alleviate the overload of field windings and keep or bring back generators under voltage control. To this purpose two control means are investigated. The first involves load tap changers, which either act in reverse direction or have their distribution voltage set-points reduced. The second control action considered is load shedding triggered by generator field currents exceeding limits. Detailed time simulations of a test system are reported.

Keywords: long-term voltage instability, load tap changer, distribution voltage reduction, load shedding

1. Introduction

In long-term voltage instability scenarios transmission voltages drop progressively under the effect of generator OverExcitation Limiters (OELs) and Load Tap Changers (LTCs). In the presence of induction motors the voltage may drop sharply once some key generators, located close to the load area, stop supporting transmission voltages, under the effect of field current limitation [1], [2].

This aspect is illustrated in Fig. 1, relative to the test system considered later on in this paper. The curves show the evolution of a transmission voltage and the corresponding load voltage under the effect of a fault cleared by permanent line opening, when a proportion of 50% of motor load is considered. As can be seen in Fig. 1.*b*, after the fault clearing, two generators exceed their field current limit (g12 and g14), and a third one (g15) is exceeding its limits under the effect of LTCs trying to bring load voltages back in their deadbands, as illustrated by the dashed line in Fig. 1.*a*. When generator limitation takes place, the voltage on the load side is dropping and the motors fail restoring their air-gap powers. As a result, they stall, and large currents are drawn from the system, causing voltages

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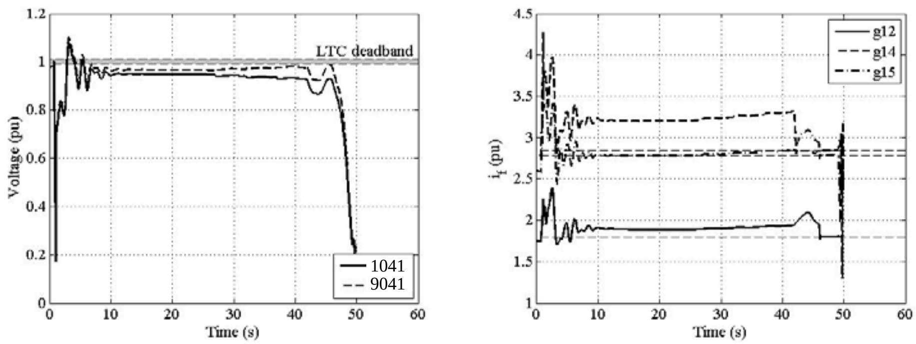
to sag even more and other motors to stall as well. It was shown in [3] how fast undervoltage load shedding can be used as an effective countermeasure.



a. *b.*

Fig. 1. Evolution of transmission and load voltages and generators field current for a proportion of 50% of motor load

As the limitation of field current in key generators significantly contributes to instability, we investigate the emergency control actions that can be used in order to prevent generators from getting their field currents limited. Among these actions, results involving modified LTC control and load shedding triggered by generators field current exceeding limits are reported.

2. Modified LTC control techniques

As is well-known, LTCs act on the ratios of distribution transformers to control the voltages at the load side. More precisely, each LTC aims at keeping the load voltage inside a deadband around the nominal value. As a result, after a disturbance, LTCs restore the powers of the voltage dependent loads to their pre-disturbance values. This behavior is beneficial for customers under normal operating conditions, but when facing severe disturbances the LTCs action may lead to instability and voltage collapse [4]. In order to counteract this behaviour several emergency LTC control actions exist, such as: tap blocking, tap return to a predefined position, tap reversing, and distribution side voltage set-point reduction.

Out of these LTC control techniques, tap reversing and set-point reduction are the ones considered in the sequel. With the tap-reversing method proposed in [5], the LTC starts controlling the transmission system voltage instead of the load voltage as soon as the former drops below some threshold. With the set-point reduction method, the reference voltage of the LTC is lowered by a predetermined value, also upon detection of a low transmission voltage [6]. In both cases, the LTC operation leads to the decrease of the load voltage and thus a decrease in the voltage dependent load powers drawn from the transmission system. This contributes to relieving the generators field currents.

The idea demonstrated in this paper is to use a signal stemming from generators exceeding their field current limits in order to trigger LTC reverse operation or distribution voltage set-point reduction. In the tests we considered a typical LTC response time in normal operating conditions, with a step change every 10 s and an initial 20 s delay for the first tap change, as long as the monitored voltage is outside the deadband. However, upon reception of the emergency signal from generators, the LTC is assumed to have a faster response; this is motivated by the fact that the field current can exceed its limit only for a limited period of time. It was thus considered that the LTC could perform one tap change every 5 seconds in those emergency conditions.

3. Load shedding

Load shedding is a cost-effective countermeasure against voltage instability triggered by large disturbances. To this purpose some event-based and response-based protection schemes against short- and long-term voltage instability have been successfully developed and tested [7-10]. The most important settings of an undervoltage load shedding scheme are the voltage threshold below which load shedding action is enabled, the delay before loads are effectively disconnected and the amounts of load shed. This paper reports on an alternative scheme in which load is curtailed to avoid generators from being switched under constant excitation and hence, to keep or to bring them back under automatic voltage control. In these tests it was assumed for simplicity that load shedding is performed in steps with constant time delays and amounts of curtailed power. In a typical long-term voltage instability scenario, the transmission voltages stay at normal value for some period of time after the initiating disturbance. Thus, undervoltage load shedding has to wait until voltages assume abnormally low values. Better anticipation capability is expected from the monitoring of generator field currents. The load buses eligible for shedding should be chosen among the ones located close to the overexcited generators. The best location could be identified more accurately from sensitivity analysis. The load shedding action starts when a monitored generator has its field current above the limit for some time. Then, loads are disconnected as long as the current remains above the limit. If the current cannot be decreased fast enough and the OEL acts to protect the generator, the scheme keeps on shedding load until the generator is brought back under voltage control.

Furthermore, in the tests presented in the sequel, the undervoltage load shedding scheme detailed in [3] is considered as a back-up protection in case the new proposed control techniques would fail restoring transmission voltages.

4. Test system

The proposed combined control actions were tested on the Nordic32 test system [3]. Its one-line diagram is shown in Fig. 2.

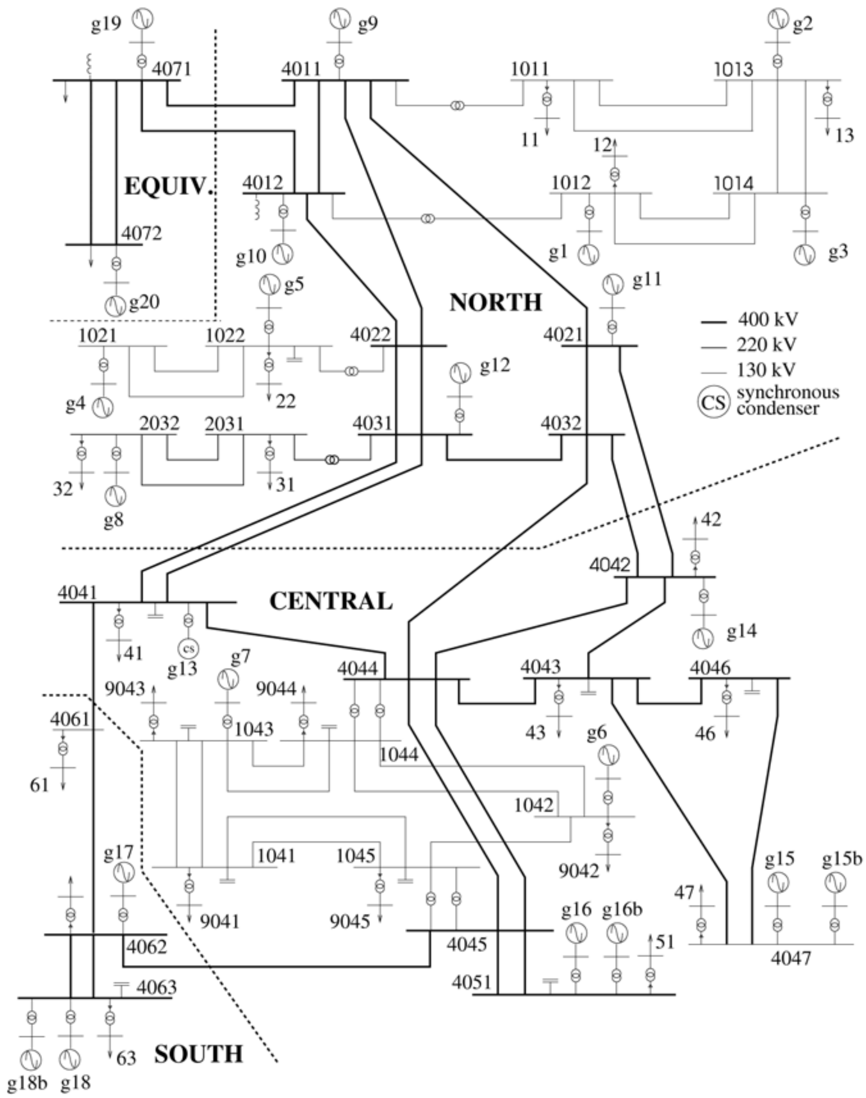


Fig. 3. Nordic32 test system

The model includes 55 buses, 20 generators, and 22 loads. The long-term dynamics are driven by LTCs and OELs acting with various delays. The generators are provided with an excitation system that takes the lowest among the AVR and

OEL signals. Hence, when load shedding brings relief to the generator, the OEL resets and the AVR regains control with negligible delay. All loads are connected to MV distribution buses controlled by LTCs. The load shedding controllers are placed in the "Central" area where the largest voltage drops are observed, monitoring the HV buses 1041, 1042, 1043, 1044, and 1045. The tests involved a proportion of 50 % of motor load.

The tests involved various outages of lines connecting the "North" and "Central" areas. In all cases, the disturbance consists of a short-circuit applied on the line, very close to one of the end buses, at time instant t = 1 s and cleared after 0.1 s by opening the line at both ends.

5. Results

Before testing the proposed combined control, the undervoltage load shedding detailed in [3] was tested for reference purposes. This scheme alone succeeds stabilizing the system by curtailing a total of 276 MW. The resulting voltage evolution is shown in Fig. 3.

The operation of the LTCs acting to preserve transmission voltages is illustrated in Fig. 4. As can be seen the reverse action leads to a decrease in load voltage (dashed line in Fig. 4.*a*) and a relief in generators field currents. However, even though the combined effect of all LTCs prevents generator g15 from having its field current limited, the same does not hold true for generators g14 and g12. Nevertheless the system is stabilized. In fact, its voltages settle at a constant value due to the fact that the transformers reached their maximum tap position. However, the system is stabilized at the expense of load voltages reaching unacceptably low values.

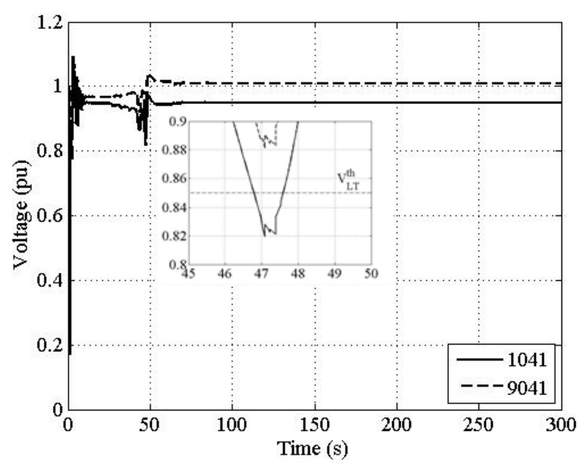


Fig. 3. Evolution of transmission and load voltage with undervoltage load shedding enabled

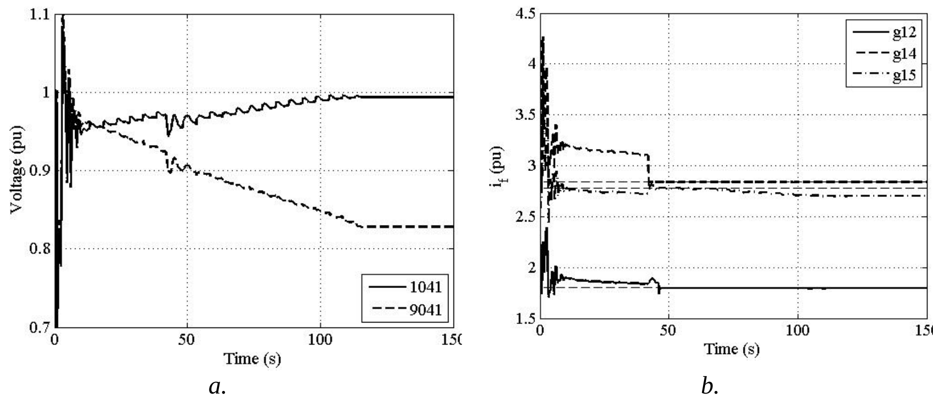
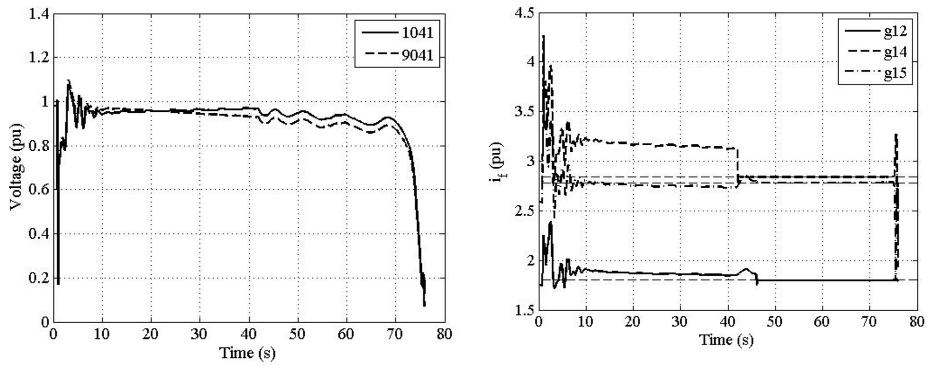


Fig. 4. Evolution of transmission and load voltages and generators field current with LTCs reverse action

The second LTC control logic consists of reducing the voltage set-point by 5% (thus bringing it to 0.95 p.u.) as soon as the generators exceed their field current limits. As can be seen from Fig. 5, this action is not strong enough, and the system is no longer stabilized. Generator g15 has its field current initially brought below the limit but it exceeds the latter again when the other generators get limited.

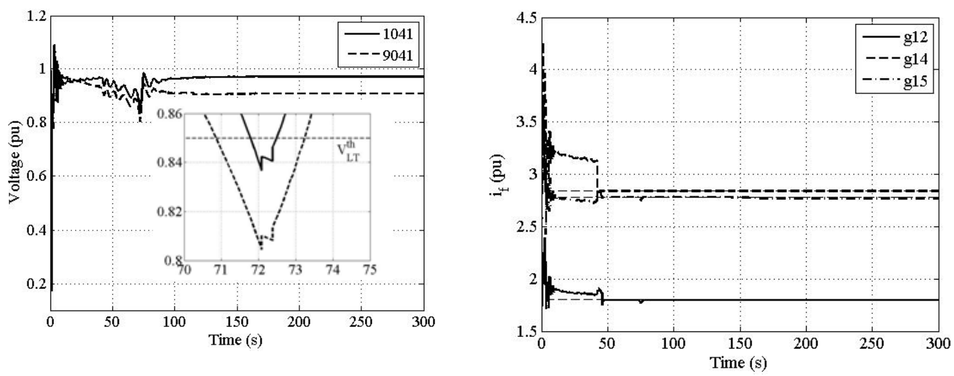
In this case the back-up undervoltage load shedding is triggered and it stabilizes the system as illustrated by Fig. 6. A total amount of 67.5 MW is shed. This shows that, despite the fact that LTCs by themselves do not succeed stabilizing the system, their action yields a decrease in the amount of load shed: indeed, in the same case without LTCs action, 267 MW of load were shed (see Fig. 3).

Figure 7 illustrates the performance of load shedding based on generator field currents. Each load shedding controller curtails small blocks of 5 MW each 5 s as long as the field currents are exceeding limits or the generators are not brought back under voltage control. As can be seen in Fig. 7.*b* the load shedding action is more effective, since generators g12 and g15 are prevented from getting limited, while generator g14 is brought back under voltage control after a while. These results are obtained at the expense of 450 MW shed.



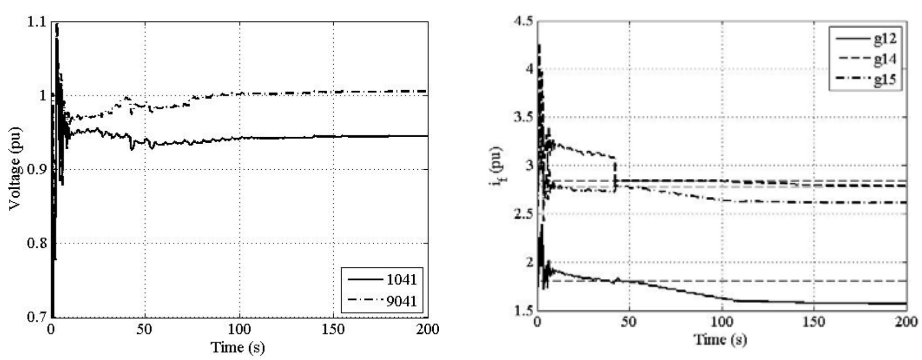
a. *b.*

Fig. 5. Evolution of transmirssion and load voltages and generators field current with LTCs reduced set-point



a. *b.*

Fig. 6. Evolution of transmission and load voltages and generators field current with LTCs reduced set-point and undervoltage load shedding

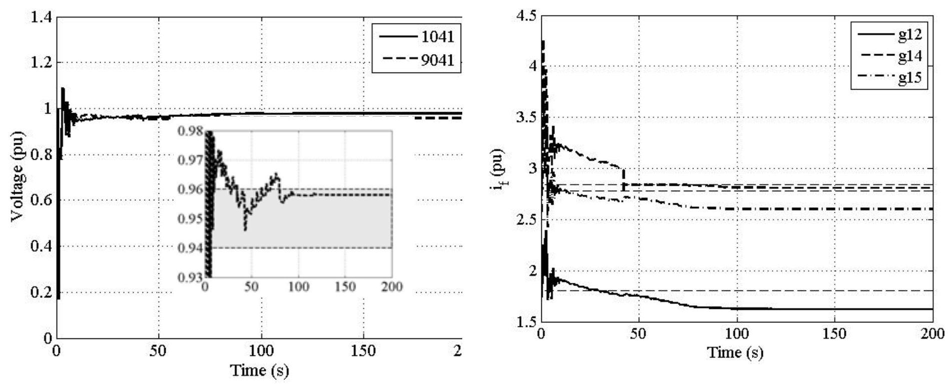


a. *b.*

Fig. 7. Evolution of transmission and load voltages and generators field current with load shedding triggered by generator field current exceeding limit or limitation

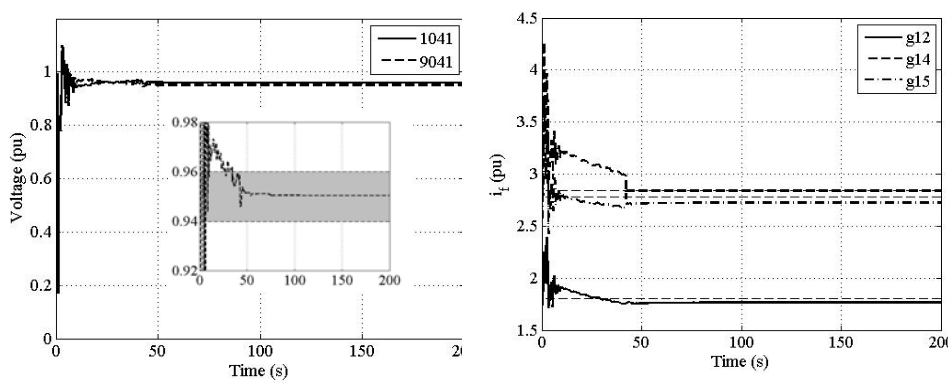
The set of results, shown in Fig. 8, was obtained with both emergency control actions combined. The LTCs set-points are reduced by 5% and load shedding is enabled as soon as the emergency signal is received from generator field currents. In this case 300 MW of load was curtailed. As in the previous case, the LTCs action leads to a reduction in the amount of load shedding.

Figure 9 shows the results obtained with a variant in which load shedding is enabled only by the field currents exceeding their limits; thus, load shedding is stopped when the generators get limited by the OELs. In this case, the load shedding amount is reduced to 150 MW, but the system is in a weaker operating condition with g14 not controlling its terminal voltage.



a. *b.*

Fig. 8. Evolution of transmission and load voltages and generators field current with LTCs reduced set-point and load shedding triggered by generator field current exceeding limit or limitation



a. *b.*

Fig. 9. Evolution of load voltage and generators field current with limited LTC reverse action and load shedding triggered by generator field current exceeding limit

6. Conclusions

Two control actions aimed at counteracting long-term voltage instability in the presence of induction motors were presented.

The LTCs reverse action could save the system but at the expense of unacceptably low voltages experienced at load buses, and assuming that the range of transformer ratio available for control was large enough. The LTCs set-point reduction cannot prevent voltage collapse, but if this control action complements an undervoltage load shedding scheme, it leads to a lower amount of curtailed load power.

Load shedding triggered by generator field currents exceeding their limits is an effective measure, but it can lead to important amounts of load shed (e.g. in comparison with the undervoltage load shedding protection scheme) especially if the control is applied until all generators have regained control of their voltages. Nevertheless, in combination with the LTCs set-point reduction technique, the amount of load shed is reduced.

Acknowledgements

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