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基于最优潮流的二级和三级电压控制

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摘 要 基于实时的最优潮流提出一种合并的二级和三级电压控制方法,该方法能够周期性地刷新发电机电压调节器的参考电压。以最大负载能力为目标的最优潮流被用来实现所提控制方法。能够周期性地刷新发电机压调节器的参考电压。以最大负载能力为目标的最优潮流被用来实现此控制为法。所提技术的对比对象是“经典”的二级电压控制,其先导节点参考电压通过负载能力最大的最优潮流(三级电压控制)计算得到。在新英格兰 10 机 39 节点上所进行的不同运行条件和紧急状态下的时域仿真验证了所提二级和三级电压控制合并方案的有效性,并且展现了对于现有二级和三级电压控制的优势。

关键词 电压稳定 二级电压控制 三级电压控制 最优潮流 最大负载能力

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Voltage control in power networks includes three hierarchical control levels: primary voltage regulation (PVR), secondary voltage regulation (SVR), and tertiary vltage regulation (TVR)[1—4].

Typically, SVR consists on controlling the voltage of a given "pilot" node/bus in the voltage control area through hardware that dynamically adjusts the set points of the area PVR controls at a "slower" speed. One of the main issues with SVR is the determination of the voltage control areas and associated pilot buses[1], since as voltage control areas change with system conditions and/or growth, the voltage control areas and associated pilot buses need to be properly redefined. Hence, a more flexible approach to SVR that readily adapts to system changes is needed. The OPF-based SVR + TVR methodology proposed in the current paper addresses this particular issue, since the method is basically software based.

TVR concerns the determination of "optimal" set points for the SVR pilot buses based on centralized OPF computations, which periodically (typically every 30 min—1 h) adjust the pilot buses' set-points to, for example, minimize system losses or maximize system loadability[1].

The proposed SVR + TVR technique integrates the TVR into an OPF problems solved every few seconds, "relaxing" the inequality constraints of the associated optimization model by neglecting certain operating limits that are not quite relevant to the voltage control problem. Thus, in the present work, the SVR and TVR are basically combined into one control scheme in which Maximum Loadability (ML) OPFs are solved in real-time (every 30 s), directly yielding the optimal set points of the PVR controls for the given system conditions for each region. This OPF approach, as with "standard" SVR and TVR approaches, results in an increased loading margin and associated enhanced system voltage stability[5—8]. The OPF problems are solved using an interior-point method approach given the demonstrated computationally efficiency and robustness of this optimization solution method[9].

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1 SVR and TVR Background

As explained in detail in reference[1], SVR is based on dividing the large power system into several voltage control regions, with the voltage magnitude of a "central" load bus, referred to as pilot node/bus, being coordinately controlled by a selected set of generators in the region. The main objective of SVR is to control the pilot bus voltages by basically adjusting the set points of the regional generators' AVRs in a coordinated way with respect to their reactive power reserves. TVR complements SVR by periodically defining the pilot bus voltage set points for all voltage control regions based on centralized OPF studies.

In the Italian system[10,11], TVR is realized through a periodically run OPF, defining the optimal voltage set-points at the SVR pilot buses. The SVR is realized by means of reactive voltage regulators (RVRs), which directly control the voltage magnitude at the regional pilot nodes, and Q (Reactive Power) Regulators (QRs), which using a regional q level signal ($-1 \leqslant q \leqslant 1$) from the RVR controls the reactive power (Q_G) levels for each participating generator in the region with respect to its Q-limits (Q_{Gl}), modifying the set-points of the AVRs to produce effective reactive power support. The RVR and QR are illustrated in fig. 1, where V_{Pref} represents the reference pilot bus voltage set by the Control Center; X_{TG} represents the generator's transformer reactance; X_{eq} is the equivalent reactance between the generator plant's bus and the pilot bus, which can be readily computed from the bus impedance matrix (the inverse of the bus admittance matrix); T_G is the QR PI-block time constant, which is typically set to 5 s; Q_G is the generator's reactive power output; and Q_{Gl} stands for the generator reactive power maximum or minimum limit, depending on whether the generator is over-or under-excited, respectively. The K_P and K_I parameters of the PI-blocks are calculated as follows:

$$K_P = 1/(Q_{Gl}X_{TG}) \tag{1}$$

$$K_I = (1 + K_P Q_{Gl} X_{eq})/(T_q Q_{Gl} X_{eq}) \tag{2}$$

where T_q is a time constant typically set to 50 s.

Besides the obvious clustering of buses by geographical location, there are various other techniques to identify the voltage control area and their associated pilot buses. In reference[12], two techniques are proposed for grid decomposition, namely, the bus impedance matrix and sensitivity coefficients representing how voltage variations on one bus affect another bus. Therefore, the voltage control areas are affected by both system topology and conditions, and hence these areas change dynamically during system operation, which is an issue with the current SVR approaches, which assume that these areas remain fixed. This particular problem is addressed by the proposed SVR + TVR technique, as discussed next.

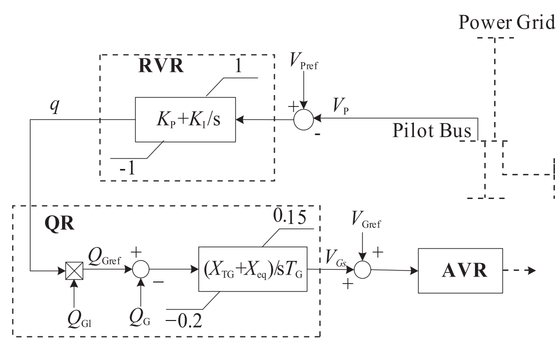

Fig. 1. Generator SVR controller scheme used in the Italian system

2 Proposed Voltage Control Scheme

As mentioned in the first section, the proposed idea is to replace the SVR and TVR by OPFs that are solved at regular time intervals comparable to the time response of "standard" SVR controls (*e.g.* every 30 s); the solution of these OPFs define the reference voltages of AVRs periodically. The OPF model considered here for the proposed SVR + TVR control is the following ML approach[13]:

$$\begin{aligned} \max \quad & \text{Loading Margin} = \lambda \\ \text{s.t.} \quad & g(V, \delta, Q_G, \lambda, K_G) = 0 \\ & Q_{Gi\min} \leqslant Q_{Gi} \leqslant Q_{Gi\max}, \forall i \in \mathcal{G} \\ & V_{i\min} \leqslant V_i \leqslant V_{i\max}, \qquad \forall i \in \mathcal{B} \end{aligned} \tag{3}$$

where $\mathcal{G}$ and $\mathcal{B}$ stand for the set of generator buses and system buses, respectively; $g(\cdot)$ corresponds to the standard power flow equations; V stands for the vector of unknown bus – voltage magnitudes; and δ is the vector of unknown bus – voltage angles. The variable λ stands for the loading factor and K_G is a variable used to model a distributed slack bus approach, as per the following general definitions:

$$\begin{cases} P_G = (\lambda + K_G) P_{Go} \\ P_L = \lambda P_{Lo} \\ Q_L = \lambda Q_{Lo} \end{cases} \tag{4}$$

where P_{Go}, P_{Lo} and Q_{Lo} represent the base values of active power generation, and active and reactive power demand, respectively, which in the proposed scheme correspond to the generation and load values obtained from a state estimator (SE) at the time when the OPF solver is activated.

It is important to highlight the fact that in this optimization model, no other limits such as generator active power limits or transmission – line limits, which are typical operating limits considered in standard OPF models, are taken into account, since these limits are not that relevant to the voltage control problem at hand.

Figure 2 illustrates the overall structure of the proposed scheme. Observe that measured data from a SCADA system are sent to an SE, which provides on-line estimations of required system variables. These data are fed into the regional OPF solvers to compute the optimal control actions. The Clock signal controls the time intervals at which the OPF is solved.

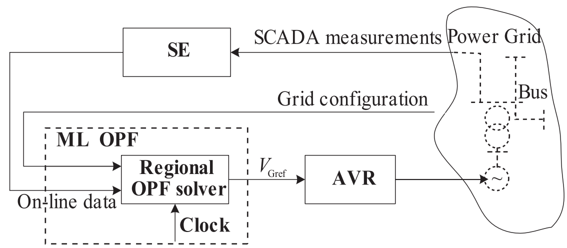

Fig. 2 Overall structure of the proposed SVR + TVR scheme

3 Results

Numerical comparisons between the “classical” SVR with TVR controls, and the proposed regional SVR + TVR schemeare are presented. The test systems discussed here is the New England 10 – machine, 39-bus system[14]. Time domain simulations are performed using PSAT[15], which is a popular MATLAB toolbox for static and dynamic studies. All studies were performed on an IBM server with 4-Intel Xeon 2.8 GHz processors with 32 GB RAM and running 32-bit MS Windows.

Figure 3 depicts the simulation process of the proposed control scheme, where S_1 stands for the signal used to activate the optimization solver (every 30 s starting at 20 s), and S_2 is the signal used to define the point at which the control set points are changed (every 30 s starting at 30 s); this assumes that the OPF can be solved in the span of 10 s. The ML OPF model is solved using AMPL[16],with the interior – point – method solver KNITRO[17].

The generators were modeled using a 4th – order model, with IEEE type-1 AVR and turbine governor controls[15]. A constant power (PQ) load model is assumed to simulate step load changes and thus force the system to a voltage collapse condition. It is important to highlight the fact that these PQ load models were used here since it was not possible to properly simulate base-load step changes as well as load recovery processes, which are required to drive the system to collapse[3], using existing load recovery models such as those proposed in, for example[18], as the base – load voltage is unknown in this process.

The pilot node is selected based on its short circuit level, as explained in the first section, i. e. the load node with the largest short circuit capacity is selected as the pilot node; this results on Bus 20 being selected as the pilot bus. In this case, only the generators connected at Bus 31, 32, 33, 34, 35 and 36 are assumed to participate on the SVR and TVR controls, since other generators do not have a significant effect on the pilot bus voltage.

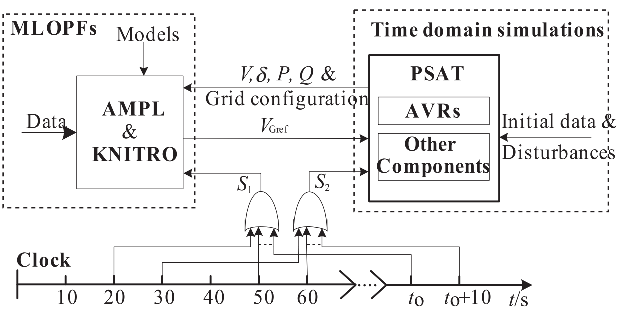

Fig. 3 Simulation process of the proposed control scheme

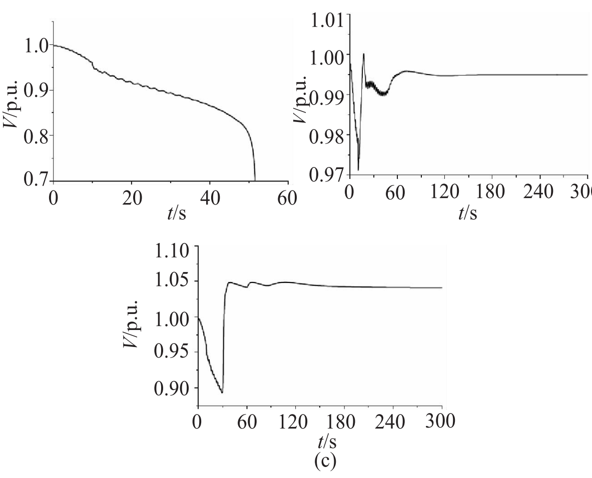

Fig. 4 Voltage profiles at Pilot Bus 20 for Disturbance 1 in the 39-test system

The TVR process associated with the "classical" SVR control approach defines the initial set point for the pilot bus, since the TVR OPF model is typically solved every several minutes (*e. g.* 30 min to 1 h), as per standard operating practices. The ML – OPF model was used in the TVR scheme, assuming the bus – voltage magnitudes to be within 1.1 and 0.9, with the generator reactive power limits being defined in the system database.

In the contingency case, the loads were increased by 1% steps with respect to their base value every second between 1 s and 9 s; this yields a 9% total load increase in the system in the span of 9 s. At 10 s, Line 8 – 9 was tripped.

Figure 4 illustrates the voltage magnitude profiles at Pilot Bus 20 for the studied disturbance. In figure 4, p. u. is the abbreviatipn of per unit. Observe in fig. 4 (a) the voltage collapse when no SVR and TVR controls are active. On the other hand, figs. 4 (b) and (c) show the proper system recovery when SVR and TVR controls are active, with the proposed SVR + TVR resulting in faster recovery and better overall voltage profiles, i. e. higher voltages and lower oscillations.

Table 1 illustrates the proposed optimization results for the ML – OPF approach. Observe the varying set – points of the terminal voltages for the generator buses (note that the actual set points of the corresponding AVRs are higher due to their control droop), which in most cases are significantly different from the corresponding ones in normal operating conditions; after the third OPF solution at 90 s, the system is practically recovered, and hence the OPF solutions do not change. Notice that the CPU times for solving the related OPF problems are all well within the allowed 10 s solution interval, and no OPF convergence problems were observed, as expected.

Table 2 illustrates the steady-state total reactive power generation increments with respect to the initial generator outputs at normal operating conditions for the different kinds of controls. Observe that the classical SVR and TVR yield higher outputs.

Table 1 Results of ML - OPF SVR + TVR Approach

	Normal Conditions	S_2 30 s	S_2 60 s	S_2 90 s +
λ	2.185	1.698	1.677	1.671
CPU/s		0.016	0.016	0.015
V_{G30}	1.048	1.100	1.100	1.100
V_{G31}	1.000	1.040	1.038	1.038
V_{G32}	0.983	1.035	1.034	1.033
V_{G33}	0.997	1.100	1.100	1.100
V_{G34}	1.012	1.091	1.090	1.090
V_{G35}	1.049	1.100	1.100	1.100
V_{G36}	1.064	1.100	1.100	1.100
V_{G37}	1.028	1.100	1.100	1.100
V_{G38}	1.027	1.100	1.100	1.100
V_{G39}	1.030	1.084	1.084	1.084

Table 2 Total Qg Increments in Steady S tate after Contingency

	Classical SVR & TVR	Proposed SVR + TVR
ΔQg(MVar)	354	245

4 Conclusions

The combination of SVR and TVR controls based on a regional and periodical ML OPF approach was proposed and discussed. The proposed approach was tested and compared using the New England 10-machine 39-bus test system.

The presented results and discussions demonstrate the feasibility and advantages of the proposed combined SVR + TVR approach with respect to existent SVR and TVR controls. Since the method is mainly software-based, the voltage control areas can be readily redefined to better reflect changes in the system operating and/or topological conditions. The voltage profiles at all buses are better overall, with all voltages being maintained within required steady-state limits; this is mainly due to the periodical optimization of the system voltages.

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Secondary and Tertiary Voltage Regulation Based on Optimal Power Flows

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[**Abstract**] A combined secondary and tertiary voltage regulation (SVR + TVR) methodology based on real-time optimal power flows (OPFs) is proposed to periodically update the generators' voltage regulator set points. A maximum loadability (ML) OPF approach is used for the proposed SVR + TVR control. The presented technique is compared against a "classical" SVR control, where the pilot-bus set points are determined by means of a ML-OPF-based TVR approach. Time domain simulations of the New England 10-machine 39-bus system for various operating conditions and contingencies are used to validate the proposed SVR + TVR technique, and to demonstrate its advantages with respect to existent SVR and TVR approaches.

[**Key words**] voltage stability secondary voltage regulation tertiary voltage regulation optimal power flow maximum loadability