Comparison of active and reactive power control for improvement of power system stability

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Summary

Active and reactive power compensators can be used to damp power oscillations within an electrical network occuring after a fault. An optimal control strategy for these elements is presented in state space. Furthermore, it is shown how this strategy can be implemented using local measurable signals. Another aspect deals with the application of FACTS for improvement of transient stability. A coordination of the requirements in optimal damping and maximal transient stability using active or reactive power control is discussed.

Key words:
SVC, SMES, FACTS, transient stability

1. Introduction

Disturbances in electrical networks lead to transient effects like damped oscillations between the generators. If the power angle becomes to large this can cause the loss of synchronism. Otherwise, if the system is able to return to a stationary operating point, this ability is called the transient stability. During the last years the growth of the rated power of generating units, the increasing loads of the interconnection lines and the strong influence of fast voltage regulators haven worsen the system damping and by this means the transient stability was affected in the same way. To improve the damping of power oscillations, active power storage units (e.g. batteries, SMES /1, 2/) and reactive power compensators (SVC /2, 3/) can be used. These elements are connected to the net via power converters /4/. In this paper it is shown, how the compensators must be controlled in an optimal way to obtain a maximal damping of the power oscillations occuring after a fault. Furthermore, the use of FACTS (flexible AC transmission systems) for an improvement of transient stability is discussed. /5/

2. Optimal control strategy for damping of power oscillations

The optimal control strategy is obtained, applying the direct Lyapunov method. With this method, the behaviour of the system's equilibrium point is examined in state space. To find out whether the trajectory remains in the close environment of the stationary point, a **Lyapunov function V(x)** must be examined. This function is positive definite ($V(x) \geq 0$) in the environment of the equilibrium point and its derivation is negative definite ($V'(x) \leq 0$). These conditions are fulfilled for example by the energy of the system. It is defined by: /6/

$$V(\delta,\omega) = E_{Kin} + E_{Pot} \qquad (1)$$

In this equation the kinetic energy E_{Kin} and the potential energy E_{Pot} are calculated as follows:

$$E_{Kin} = \frac{1}{2}\sum_{i=1}^{n} M_i \omega_i^2 \qquad (2)$$

$$E_{Pot} = -\sum_{i=1}^{n}\left[P_{mi} - P_{0i}^{0}\right]\left[\delta_i - \delta_i^s\right] - \sum_{i=1}^{n-1}\sum_{j>i}^{n} b_{ij}\left[\cos\delta_{ij} - \cos\delta_{ij}^s\right] \qquad (3)$$

In equation (3) the angle δ^S describes the equilibrium point towards which the trajectory is moving after the occurrence of a fault.

By minimizing the Lyapunov function the optimal strategy can be obtained. This optimal control forces the fastest dissipation of the energy involved to the system during a fault. The active power at the node k is controlled by: /6/

$$G_S(t) = K\left[\sum_{i=1}^{n}\omega_i \sum_{j=1}^{n}\beta_{ik}\beta_{kj}\cos\delta_{ij}\right] \qquad (4)$$

Equivalently, the optimal strategy for reactive power control of a compensator located at the node k is obtained by: /6/

$$B_S(t) = K\left[\sum_{i=1}^{n}\sum_{j>i}^{n}\beta_{ik}\beta_{kj}\omega_{ij}\sin\delta_{ij}\right] \qquad (5)$$

with $\beta_{ik} = X_{SHC}B_{ik}|E_i|$

In equations (4) and (5) the regulator gain is described by K and the short-circuit reactance of the net by X_{SHC}. It can be seen, that the active power control depends on the absolute slip ω_i, whereas the reactive power control is determined by the relative slip ω_{ij} between the generators i and j.

3. Local measurable quantities for active and reactive power control

Optimal strategy for active and reactive power control obtained by Lyapunov method (equations (4) and (5)) depends not only on parameters of the network but also on state variables power angle δ and power angle velocity ω. These quantities are not or only with considerable efforts measurable (e.g. an observer). To implement the optimal control, it is necessary to find local measurable electrical signals that imitate the strategies as exact as possible. The electrical quantities should not depend very much on the controller's action because otherwise the so called "hunting-phenomenon" occurs. These are high-frequency oscillations caused by the feedback between the control and the measuring signal mainly when bigger regulator gains are used.

Various simulations have shown a couple of signals, suitable for active and reactive power control. Good results have been obtained using the frequency deviation ($d\theta/dt$) for active power control. For an installation of the storage unit close to the generator the transmitted active power P_A appeared to be a suitable measuring signal. The according control strategy is described by: /6/

$$G_{S1}(t) = 2K|U|^2\frac{d\theta}{dt} \qquad (6)$$

Respectively, for an installation close to the generator we obtain:

$$G_{S2}(t) = K\frac{d\left[2P_A - P_S\right]}{dt} \qquad (7)$$

The storage power P_S in algorithm G_{S2} (equation (7)) is needed to reduce the sensitiviy of the measuring signal P_A against the hunting-phenomenon.

The electrical quantities presented above only show good results when used for active power control. For reactive power control other signals are necessary. In this case, it's also important to consider the place where the compensator is installed. If the reactive power controller is located within the network good results can be obtained using the voltage as control signal. The suitable algorithm is described by the following equation: /6/

$$B_{S1}(t) = K\left[-\frac{1}{2}\frac{d|U|^2}{dt} - X_{SHC}\left(-|U|^2\right)\frac{dB_S}{dt}\right] \qquad (8)$$

The feedback of the control signal $B_S(t)$ is needed to reduce the influence of the hunting-phenomenon. In this way the regulator gain K can be increased in such a manner that for significant amplitudes of the power oscillations bang-bang behaviour occurs.

If the compensator is installed at a generator node, the following algorithm can be used for reactive power control: /6/

$$B_{S2}(t) = K\frac{d\,Q'_A}{dt} \qquad (9)$$

In this equation Q'_A stands for the generator's reactive power minus the losses in the generator reactance X'_d.

4. Simulation results for damping of power oscillations

For the following test system (figure 1) the differences between active and reactive control for damping of power oscillations are shown. The network consists of two generators G1 and G2 which are connected to the infinite bus G3.

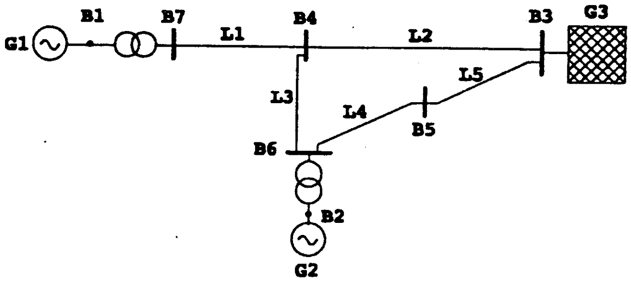

Figure 1: Structure of test system 1

A three-phase short-circuit in line L4 with a duration of 120 ms and a post-fault switching-off of the line leads to power system oscillations that should be damped using active and reactive power compensators. Different inertia constants of the generators and the structure of the network causes two oscillation modes. The mode with the higher frequency belongs to the oscillation between G1 and G2 (local mode), whereas the slower mode belongs to the oscillation of the generators against the infinite bus (interarea mode).

In figure 2 the results are presented when the compensator is installed in node B6. The active power control was realized with the algorithm G_{S1} (equation (6)) and for the reactive power control the strategy B_{S1} (equation (8)) was used. In both simulations the controllable compensator power remains the same (11.4 % of the power of generator G1).

It can be seen that the application of a compensator improves the system damping significantly. The influence of the active power control on the power oscillation is much stronger than the reactive power control when using the same rated compensator power. Already the first halfwave of the oscillation is well damped using active power control. The slow oscillation mode is completely suppressed after 4 seconds, the fast mode after 7 seconds. The influence of reactive power control on the different oscillation modes is much weaker. For this reason the power oscillation isn't completely damped after 7 seconds.

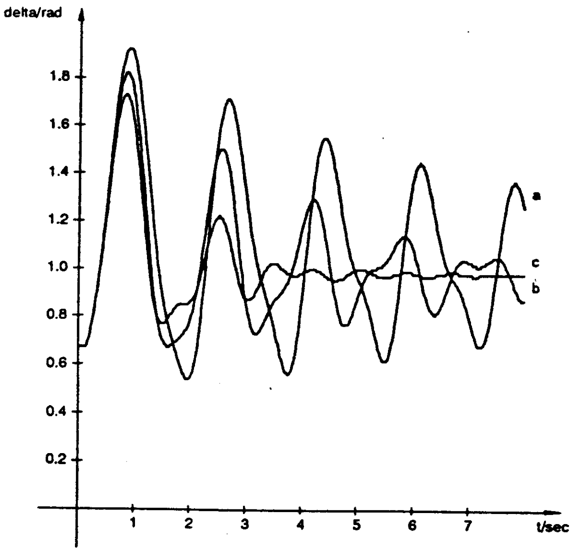

Figure 2: Power oscillations of generator G1

a: without compensator

b: reactive power control

c: active power control

Essentially for the effectiveness of the control strategies is the location of the compensator within the network. As a result of the superposition of the different oscillation modes it is not possible to damp all of them in an optimal way, because by the reason of the differing frequencies a different control rate must be required. In figure 3 the differing effectiveness of the control strategy G_{S1} (equation (6)) is shown for different locations of the compensator. It clearly can be seen that the damping in node B6 is much stronger than in node B4. The oscillation mode against the infinite bus is well damped. If the compensator is installed in node B4 the mode between the two generators G1 and G2 can not be properly damped because the active power storage unit is located near the electrical center of the network. This means, the fast oscillation mode is not controllable in node B4.

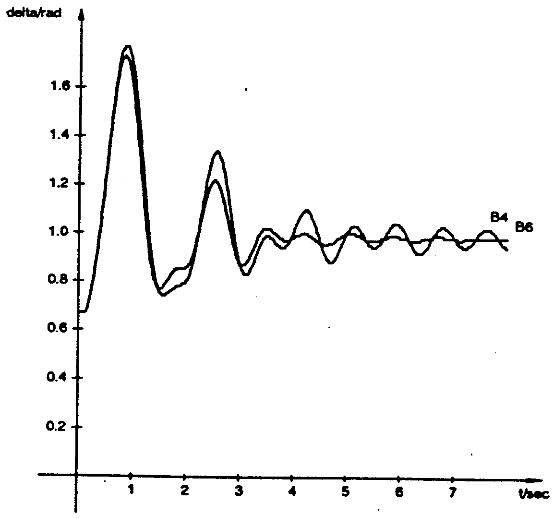

Figure 3: Active and reactive power control in nodes B4 and B6 of test system 1

5. Improvement of transient stability through active and reactive power control

The power oscillations after the occurance of a fault can lead to the loss of synchronism of the system. The ability of the system to maintain the synchronous point is called the transient stability. An improvement can be obtained by using FACTS (flexible AC transmission systems). The improvement of transient stability competes with the optimal damping of power oscillations. Here, the influence of active and reactive power control on transient stability shall be shown.

As an easy example the test system 2 in figure 4 is used for the following investigations. The system consists of a generator that is connected to the infinite bus via a transformer (reactance x_{Tr}) and a line with the reactance x_L. The compensator is installed on the high-voltage level of the transformer. For the given network parameters the short-circuit reactance for this location point has the biggest value and thus the influence of the compensator is maximal.

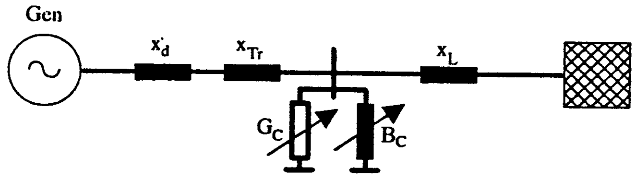

Figure 4: Structure of the test system 2

The stationary power angle of the given test system (figure 4) is ϑ_0 = 47°. A short-circuit within the network causes the acceleration of the generator's rotors. If the short-circuit isn't switched off in time, the system couldn't return to a stationary equilibrium point and the generator loses synchronism. As a measure for transient stability the critical short-circuit time t_c is used. This is the time a short-circuit may last without loss of synchronism. In state-space this point of time is determined by the intersection of the system trajectory with the boundary trajectory. For the test system in figure 4 the critical short-circuit time is 133.8 ms.

Through the use of a compensator within the network the stability area could be enlarged. In figure 5 this is done for a reactive power controller B_C with 10 % of the generator's nominal power. Improvement of the transient stability is possible if the compensator acts as a capacity for $\omega>0$ and as an inductor for $\omega<0$. The critical short-circuit time for this control strategy increases up to 140.9 ms. This is an improvement of 5.31 %. Furthermore, it can be seen that the net damping also can be improved when the reactive power compensator is switched in a suitable manner. The simulation results showed that the strategy for the improvement of transient stability and the strategy for damping of power oscillations (equation (5)) is the same. The damping in figure 5 is only obtained through the use of the compensator, a damping winding of the generator is not observed here.

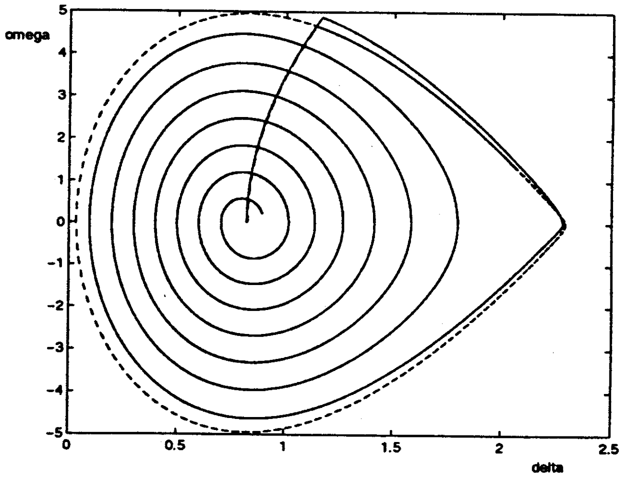

Figure 5: Trajectory for reactive power control (dashed line: boundary trajectory of uncontrolled system)

A further improvement of the transient stability and of the damping can be obtained using an active power compensator G_C instead of a reactive power compensator. In this case, the critical short-circuit time is 151.8 ms. This is an improvement of 13.45 %. Furthermore, in figure 6 it can be seen that the damping when using an active power compensator is much stronger. After a few switchings of the bang-bang regulator the equilibrium point is reached.

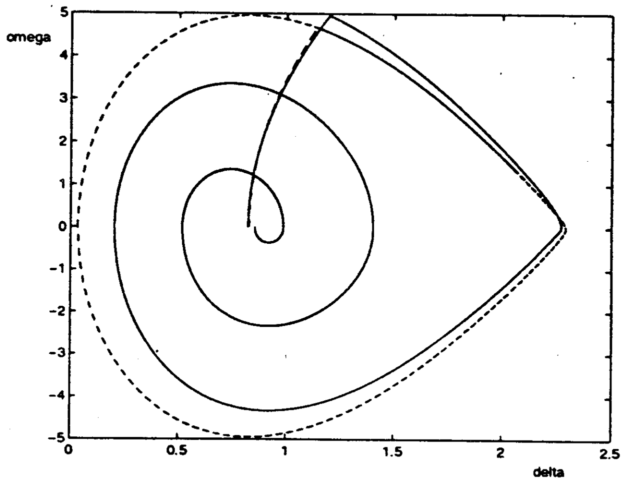

Figure 6: Trajectory for active power control (dashed line: boundary trajectory of uncontrolled system)

6. Conclusion

In this paper, it was shown how to use FACTS to improve the dynamic facilities of electrical energy systems. For this purpose, it was distinguished between active and reactive power compensators. Control strategy for damping of power oscillations have been presented. These algorithms depend on electrical measurable quantities. Furthermore, the effectiveness of the controlled compensator is determined by the location where it is installed.

The second part of the paper dealt with the use of FACTS to improve power system transient stability. As a measure for the effectiveness the critical short-circuit time was used. This time could be increased by an optimal control of active and reactive power. This leads to an improvement of power system stability.

It has been shown that an optimal damping of power oscillations and the maximal improvement of transient stability can be obtained with the same control strategy. For this reason, it can be said that an optimal damping always leads to an optimal transient stability.

7. Acknowledgement

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8. References

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