

A Flexible and Temporal Integral Optimal Reactive Power Control System

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Abstract

This paper proposes a flexible and temporal integral voltage/reactive power control system. The voltage stability problem is mainly driven by the dynamics of consumers' load demand which possesses both daily periodic character and short-term stochastic character. These two aspects are specifically addressed in the proposed system comprising mainly two control components: an optimal planner and an intelligent plan adaptor. The first component, utilizing multi-stage optimal reactive power flow algorithm, can produce a schedule of voltage control actions for the following fixed period. When this predefined plan becomes unsuitable for maintaining an acceptable voltage profile because of unexpected events in real operation, the second component takes over. It synthesises the predefined plan and the current sensitivity information between control actions and voltage profiles. Then it flexibly adjusts the predefined plan to suit the new situation. A simple 9 bus test system is used to demonstrate the application of the proposed approach. This approach works well in controlling the voltage fluctuation of a typical 9-bus system and it can be easily extended to larger practical power systems.

1 INTRODUCTION

Voltage quality is an important indicator of power system quality. Because of load demand variation or equipment failure, it should be carefully monitored and maintained within acceptable limits. With the increasing demand for electric power on existing power systems and the global deregulated restructuring, the voltage control has become more problematic and difficult to handle.

The voltage control problem is mainly driven by the dynamics of consumers' load demand, which possesses a daily periodic character as well as a short-term stochastic character [1]. A practical and successful control framework must address these characters in a systematic way.

Over the last decades, the voltage/reactive power control problem has been researched extensively as a static snap-shot optimisation problem [2], but relatively few researchers have emphasized the temporal aspects of the problem. Taylor et al. [3] proposed a transition-optimised voltage

control algorithm, which considered the voltage control problem as a time-based scheduling problem so as to avoid unnecessary control actions of reactive power resources. However, it lacks flexibility in real operation.

This paper introduces a flexible and temporal integral voltage/reactive power control system. As the name implies, it considers the voltage control problem as a temporal integral problem with the added flexibility to deal with unexpected operation situations.

2 SYSTEM DESCRIPTION

A general overview of the proposed voltage control system is shown in Figure 1. It consists of three control components: optimal planner, voltage monitor, and intelligent plan adaptor. After receiving the load forecast and topology related information from SCADA (Supervisory Control And Data Acquisition), the optimal planner utilises multi-stage optimal reactive power flow to produce a predefined plan of voltage control actions for the following fixed

period (e.g. next 24 hrs). The optimal operation time for the optimal planner is at the start of the morning load trough that is a quiet time period for voltage control. The advantage is to allocate enough time to run the time-consuming mathematical optimisation algorithm of the optimal planner. Then, the predefined plan is fed into the voltage monitor and used as the operational guide for the remaining period. In real time operation, the voltage monitor is employed to continuously monitor the control effect of the predefined plan before giving the final dispatch commands. Upon detecting that the predefined plan is not suitable in a real situation, it triggers the intelligent plan adaptor. This adaptor can smartly and flexibly adjust the plan to suit the new situation based on the synthesis of the plan and the current sensitivity information between voltage control actions and the voltage profile.

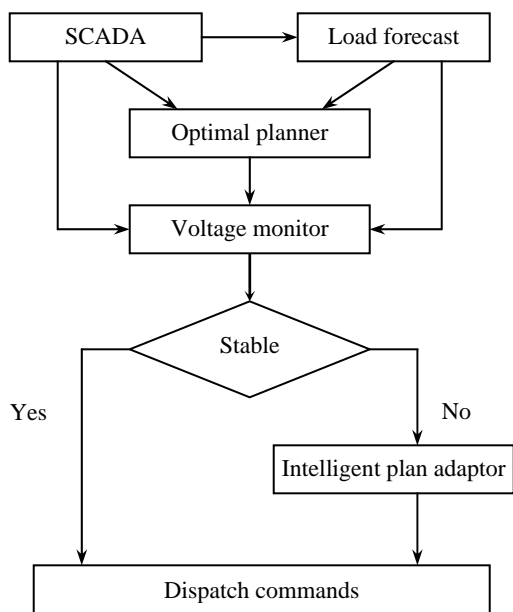


Figure 1: The voltage control system framework

2.1 The optimal planner

Optimal planner is a variation of standard Optimal Power Flow (OPF) algorithm [4]. The difference is that the proposed optimal planner considers the optimisation of voltage control for the whole planning period rather than for a snapshot as done by the latter. This reflects the real nature of the voltage control problem. For example, one important goal of daily power system operation is to keep the number of switching actions for a specific capacitor within

a reasonable range. To deal with such time-linked constraints, the approach used in this paper is to divide the continuous daily load curve into several segments according to the rate of load variation, and assume the load to be constant in every segment. Then, the status or output for every bus and reactive control equipment in every segment is represented by different variables that produces a temporal integral OPF formulation. Its objective function is to minimise the voltage control cost related to the var control in the whole planning period, which can be defined as:

$$F = \sum_{t=1}^{N_t} \sum_{i=1}^{N_i} (C_i x_i)_t \quad (1)$$

where

N_t : the number of time segments,

N_i : the number of voltage control equipment,

C_i : the unit Var cost, and

x_i : the reactive power output.

This goal is subject to time-separated constraints, such as power balance equations in every time segment, as well as time-related constraints, such as maximum allowable daily switching actions of specific capacitors. From a mathematical viewpoint, even though this formulation has high numbers of variables, it still can be solved using standard non-linear programming methods [5].

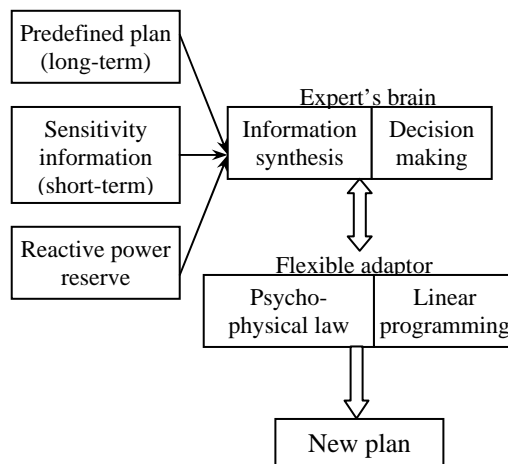


Figure 2: The intelligent plan adaptor

2.2 The intelligent plan adaptor

The intelligent plan adaptor was inspired by the experts' decision making process for solving the

voltage control problem in emergency situations (Figure 2). This expert decision process includes two important stages: information synthesis and decision making. During the information synthesis stage, the values of candidate control action under long-term and short-term criteria (Figure 2) are rated in a new, common dimension of desirability intensity for the purpose of integrating the two performance criteria. Then, the quantity of control output can be decided in the second stage. In the proposed method, the information synthesis process is emulated by Weber's psycho-physical law of 1834 [6], and the decision making process is modelled using linear programming.

The Weber's psycho-physical law of 1834 makes some human perception capabilities computable. The law asserts that the just noticeable difference in stimulus intensity must be proportional to the actual stimulus intensity itself as shown below [6]:

$$S_v - S_{v-1} = \varepsilon S_{v-1}, v = 1, 2, \dots, 7. \quad (2)$$

where $S_v - S_{v-1}$ is the just noticeable difference in stimulus intensity, S_{v-1} is the actual stimulus intensity, v is the desirability intensity, and ε is a constant ratio, which is roughly equal to 1. According to the well-known seven-point scale method (1, ..., 7) in Behavioural Science [6], the maximum value of the desirability intensity is set to seven. In simple words, the more the intensity of actual stimulus is, the more the change is needed to let human beings feel there is a difference. For example, in a bright midday sun you light a candle. Does anyone notice the effect or change in brightness due to lighting the candle? Weber's law holds that you will not notice a difference in this situation and notice a strong difference in the case that you do it in a dark night. After putting the actual stimulus intensity S_{v-1} into right side and substituting ε 's value into Equation (2), it yields the quantity relationship among the demarcation points:

$$S_v = 2S_{v-1} = 2^2 S_{v-2} = \dots = 2^{v-1} S_1 \quad (3)$$

When comparing the desirability intensity of the timing of the predefined plan in a particular time range $[T_{\min}, T_{\max}]$, the decision maker is concerned about the relative desirability than the most preferred one T_{\min} . Consequently, the actual stimulus S_v is the time increment above T_{\min} . Hence, setting the time level $T_{\min} + S_7$ at T_{\max} :

$$S_7 = T_{\max} - T_{\min} \quad (4)$$

Substituting (4) into (3)

$$S_1 = (T_{\max} - T_{\min}) / 2^6 \quad (5)$$

Now the demarcation time points are attained as the solution to:

$$\begin{aligned} T_v &= T_{\min} + S_v, v = 1, 2, \dots, 7, \quad (6) \\ &= T_{\min} + 2^{v-1} S_1 \\ &= T_{\min} + 2^{v-1} \times \frac{T_{\max} - T_{\min}}{2^6} \end{aligned}$$

Finally, the desirability intensity v can be derived from (6) as:

$$v = \log_2 \left(\frac{T_v - T_{\min}}{T_{\max} - T_{\min}} \times 2^7 \right) \quad (7)$$

The main steps of the algorithm used in the plan adaptor can be summarised as follows:

1. Perform a Newton – Raphson load flow [7] for getting the Jacobian sensitivity matrix of the current power network.
2. Compute the reactive power reserve of the generators. It indicates the current security level and decides the relative importance between short-term and long-term criteria, expressed by weights (w_1, w_2 in Equation (8)). The weights are calculated in a similar manner to v in Equation (7).
3. Transform timing information and sensitivity information into the common dimension of desirability intensity.
4. Compute new control costs for candidate control actions according to the following equation:

$$c_{new} = (w_1 \times v_t + w_2 \times v_s) \times c_e \quad (8)$$

where

- c_{new} : the new control cost,
- v_t : the desirability intensity of timing,
- v_s : the desirability intensity of sensitivity coefficients,
- w_1 : the weights for v_t ,
- w_2 : the weights for v_s , and

c_e : the original economical control cost.

5. Form the following linearised voltage control function around the operating point:

$$\min \sum_{i=1}^m c_{new} x_i \quad (9)$$

subject to

$$AX \leq B$$

where

X : the reactive power output vector,

c_{new} : the new control cost,

A : the Jacobian sensitivity , and

B : the acceptable voltage limit vector.

6. Find an optimised solution of the linearised system through linear programming algorithm.

3 CASE STUDY AND RESULTS

To verify the effectiveness of the proposed method, a modified 9-bus test system (Figure 3) developed by Matpower [5] is analysed in normal and abnormal situations. In this system, reactive power resources are available from generators at buses 1, 2, and 3, and the security voltage operation region is between 0.97pu and 1.03pu.

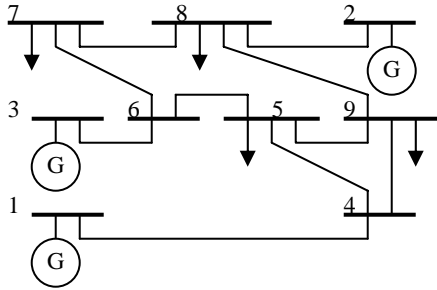


Figure 3: A 9-bus test system

3.1 Normal situation

In this case, the load demand followed the forecast pattern (forecast load in Table 1) and no other contingency happened in the power network. The optimal planner provided the following control schedule for the next one hour:

- 0 – 10 minutes:
 - set $V_{G1} = 1.03\text{pu}$, $V_{G2} = 1.03\text{pu}$, $V_{G3} = 1.022\text{pu}$;
 - dispatch $P_{G1} = 130.82\text{MW}$, $P_{G2} = 100.27\text{MW}$, $P_{G3} = 86.8\text{MW}$.

- 10 – 30 minutes:
 - set $V_{G3} = 1.026\text{pu}$;
 - dispatch $P_{G1} = 144.14\text{MW}$, $P_{G2} = 110.28\text{MW}$, $P_{G3} = 96.68\text{MW}$.
- 30 – 60 minutes:
 - set $V_{G3} = 1.03\text{pu}$;
 - dispatch $P_{G1} = 157.92\text{MW}$, $P_{G2} = 121.2\text{MW}$, $P_{G3} = 107.6\text{MW}$.

As indicated in Table 2, this control plan can remove all voltage violations and reduce the Var generation cost.

Table 1: Load level for normal (forecast load) and abnormal (real load) operation

Load bus	Forecast load			Real load
	0 – 10 minutes	10 – 30 minutes	30 – 60 minutes	0 – 10 minutes
5	90+30j	100+33j	110+36.3j	94.5+31.5j
7	100+35j	110+38.5j	121+42.35j	105+36.75j
8	0	0	0	90+30j
9	125+50j	137.5+55j	151.25+60.5j	170+52.5j

* All the values of powers are in MW

Table 2: The effect of control schedule

	Before		After	
	voltage	Var generation	voltage	Var Generation
0 – 10 minutes	$V_9=0.957$	35.5	$V_9=0.997$	12.66
10 – 30 minutes	$V_5=0.969$ $V_9=0.950$	53.1	$V_5=1.004$ $V_9=0.988$	34.16
30 – 60 minutes	$V_5=0.961$ $V_9=0.941$	76.5	$V_5=0.997$ $V_9=0.978$	59.03

* All the values of powers are in MW, voltages in pu

3.2 Abnormal situation

In the second case, an unexpected load variation was taken into consideration (real load in Table 1). The dramatic load increase caused the voltage magnitude of bus 9 to fall into an unacceptable level: 0.969pu. The intelligent plan adaptor was executed and it changed the voltage set point of generator 3 from 1.022pu to 1.026pu. The new control action successfully restored the voltage level of bus 9 from 0.969 to 0.970pu.

4 CONCLUSION

This paper proposed a flexible and temporal integral voltage control system. By extending the concept of traditional snap-shot OPF to temporal

integral OPF, a control schedule that takes time-linked constraints into account can be produced in advance. When the control schedule is not suitable due to unexpected condition changes, a flexible adaptor synthesises all the short-term and long-term control information and adjusts the predefined schedule flexibly in an intelligent manner. This control system reflects the nature of the voltage control problem driven by load dynamics and the underlying human decision making process. Simulation results show that the proposed method can effectively maintain an acceptable voltage profile in both normal and abnormal operating conditions of a typical 9-bus system. The conceptual framework proposed here can be extended to a larger power network.

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