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Design of a Graphical User Interface to Control Voltage and Reactive Power by Using Nine-area Diagram

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Abstract:For a primary substation (P/S), there are many typical methods to control voltage and reactive power such as adjusting the generator mode, switching shunt capacitor (SC), adjusting on-load tap changer (OLTC), and switching shunt reactor (SR). In this study, a graphical user interface (GUI) is designed combining with nine-area diagram to observe the relationship between voltage and reactive power in a P/S. This GUI not only predicts the effect to dispatchers in short time but also analyzes the sensitivity parameters. Field measurement data were analyzed. Simulation results confirmed the feasibility of compensating the reactive power and adjusting voltage simultaneously.

Keyword: Substations, Voltage, Reactive Power, Nine-area Diagram, Sensitivity.

1. Introduction

The voltage control methods in Taiwan are used to adjust the generator operation mode, switching shunt capacitor (SC), adjusting the on-load tap changer (OLTC), and switching shunt reactor (SR) [1]. However, the coordination between the different voltage control devices should be considered. At present, the Area Dispatch Control Center (ADCC) uses Reactive Power Devices Controller (RPDC) to assist dispatchers in controlling voltage and reactive power of a primary substation (P/S).

When using voltage control devices, the reactive power at the primary side of the main transformer (Q_1) and the bus voltage at secondary side (V_2) can be measured. Therefore, the impact on Q_1 and V_2 can be observed by using the Sequence of Event (SOE) when the SC or OLTC is adjusted.

From the measurement data, we will analyze the sensitivity parameter which can provide references to dispatchers. The sensitivity parameter database of a P/S will be calculated by using a graphical user interface (GUI) with nine-area diagram.

2. Voltage and Reactive Power Control

2.1 Nine-area Diagram

The P/S control strategy in Taiwan is "Q_1-V_2" method which can maintain the reactive power at primary side and the voltage at secondary side of a transformer in the standard range [2-3]. After setting the standard range of Q_1 and V_2, it can divide into nine-area as shown in Fig. 1. The operating strategy of the nine-area diagram is shown in Table 1. The reactive power can be based on the actual situation because it does not have a specific specification. Thus, the upper limit (Q_{max}) can be set as maximum reactive power for a P/S and the lower limit (Q_{min}) can be calculated by using the upper limit minus the maximum capacity of SCs or 1.2 times of the actual output capacity [4].

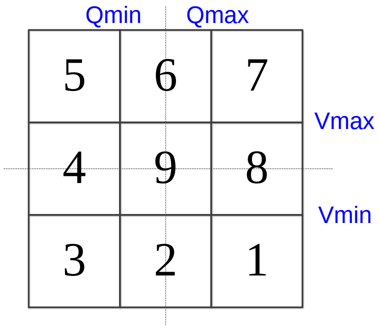


Fig. 1 Nine-area diagram of voltage and reactive power control

Table 1 The operating strategy of the nine-area diagram

Area	The status of voltage and reactive power	operating strategy
1	Voltage < lower limit Reactive power > upper limit	Switch on SC
2	Voltage < lower limit Reactive power normal	Step up OLTC tap
3	Voltage < lower limit Reactive power < lower limit	Step up OLTC tap
4	Voltage normal Reactive power < lower limit	Switch off SC
5	Voltage > upper limit Reactive power < lower limit	Switch off SC
6	Voltage > upper limit Reactive power normal	Step down OLTC tap
7	Voltage > upper limit Reactive power > upper limit	Step down OLTC tap
8	Voltage normal Reactive power > upper limit	Switch on SC
9	Voltage & Reactive power normal	**No action**

2.2 Sensitivity Analysis of Voltage Adjustment Devices

Sensitivity analysis of the voltage and reactive power control for a P/S can be expressed as

$$\begin{bmatrix}\Delta Q_1\\ \Delta V_2\end{bmatrix} = \begin{bmatrix} \frac{\partial Q_1}{\partial V_1} & \frac{\partial Q_1}{\partial k} & \frac{\partial Q_1}{\partial Q_C} \\ \frac{\partial V_2}{\partial V_1} & \frac{\partial V_2}{\partial k} & \frac{\partial V_2}{\partial Q_C}\end{bmatrix}\begin{bmatrix}\Delta V_1\\ \Delta k\\ \Delta Q_C\end{bmatrix} + \begin{bmatrix}\frac{\partial Q_1}{\partial P} & \frac{\partial Q_1}{\partial Q}\\ \frac{\partial V_2}{\partial P} & \frac{\partial V_2}{\partial Q}\end{bmatrix}\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} \qquad (1)$$

where ΔQ_1 is the variation of reactive power at primary side of transformer, ΔV_2 is the variation of the bus voltage at secondary side, ΔV_1 is the variation of the bus voltage at primary side, Δk is the percentage of variation of the OLTC turns ratio, ΔQ_C is the variation of SCs output capacity, ΔP and ΔQ are the variation of active and reactive power for loads, respectively.

Because the value of ΔV_1 is very small, it can be removed to simplify the analysis process. Moreover, the ΔP, and ΔQ are very small during 1 to 2 seconds even the OLTC and SCs are adjusted. Thus, equation (1) can be simplified as

$$\begin{bmatrix}\Delta Q_1\\ \Delta V_2\end{bmatrix} = \begin{bmatrix} \frac{\partial Q_1}{\partial k} & \frac{\partial Q_1}{\partial Q_C} \\ \frac{\partial V_2}{\partial k} & \frac{\partial V_2}{\partial Q_C}\end{bmatrix}\begin{bmatrix}\Delta k\\ \Delta Q_C\end{bmatrix} = \begin{bmatrix}a & b\\ c & d\end{bmatrix}\begin{bmatrix}\Delta k\\ \Delta Q_C\end{bmatrix} \qquad (2)$$

If the OLTC is adjusted one step, the variation of k is ±0.0125 (pu) and ΔQ_C is a constant. Thus, the sensitivity parameters, a and c, can be obtained. If switching SCs, the variation of Q_C is ±0.432 (pu) and Δk is a constant. Therefore, the sensitivity parameters, b and d, can be obtained.

3. Establish the Sensitivity Parameters Database

3.1 Analysis Results of Switching SCs in a P/S

According to a P/S monitoring data, the sensitivity parameters, b and d, can be calculated after switching SCs. In the P/S, there are five groups SCs on the 69kV bus. The capacity of each group is 43.2 Mvar. The recommended sensitivity parameters are shown in Table 2.

Table 2 The recommended sensitivity parameters in a P/S.

Sensitivity parameter	#1 SC	#2 SC	#4 SC	#5 SC	#6 SC
b	-0.788	-0.778	-0.777	-0.771	-0.748
d	0.0230	0.0220	0.0221	0.0234	0.0217

3.2 Analysis Results of Adjusting an OLTC in a P/S

According to measurement data in the P/S in winter and summer, we can obtained the sensitivity parameters, a and c, after adjusting an OLTC. There are four categories which include stepping up an OLTC in winter, stepping down an OLTC in winter, stepping up an OLTC in summer, and stepping down an OLTC in summer.

Table 3 The recommended sensitivity parameter "a" in a P/S

Q_1 before adjustment	Parameter a (Winter)		Parameter a (Summer)	
	stepping up	stepping down	stepping up	stepping down
>50 Mvar	4.425	4.425	3.899	3.707
35~50 Mvar	3.510	5.169	4.004	4.783
15~35 Mvar	3.696	4.537	3.681	4.140
< 15 Mvar	4.049	4.658	2.873	4.518

Table 4 The recommended sensitivity parameter "c" in a P/S

Q_1 before adjustment	Parameter c (Winter)		Parameter c (Summer)	
	stepping up	stepping down	stepping up	stepping down
>50 Mvar	0.820	0.820	0.823	0.838
35~50 Mvar	0.858	0.861	0.832	0.788
15~35 Mvar	0.815	0.775	0.759	0.765
< 15 Mvar	0.782	0.814	0.882	0.812

For observing the impact of reactive power in the P/S, this research assumes that the Q1 can be divided into four intervals which include more than 50 Mvar, 35~50 Mvar, 15~35 Mvar and less than 15 Mvar. The sensitivity parameters, a and c, can be obtained by using average values in each interval, as shown in Table 3 and Table 4.

4. Development of Q-V Control Program

In this section, the GUI is designed by using Visual Basic. The GUI employs the sensitivity parameter database in last section to operate easily, thus, dispatchers can determine the voltage control strategies quickly.

4.1 The Standard Range of Voltage Setting in a P/S

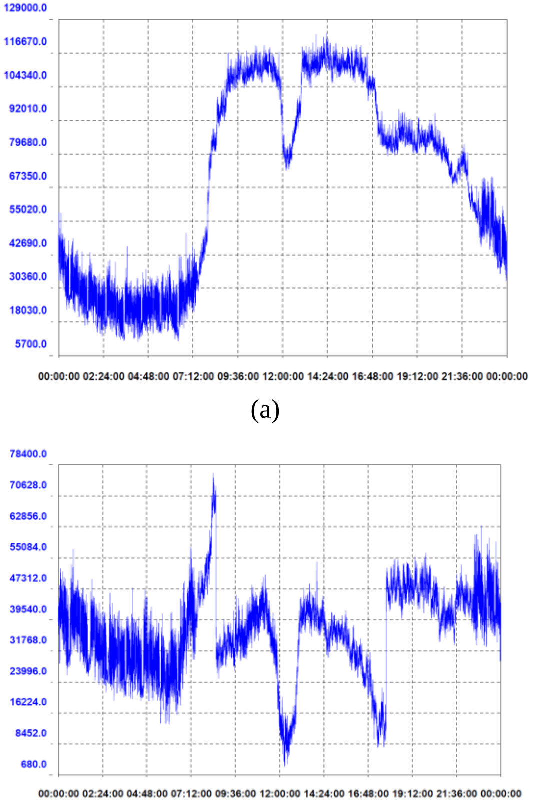
The voltage range can be obtained by using the standard voltage which is in a RPDC multiplied by ±1.5%. The standard voltage is shown in Table 5.

Table 5 The standard voltage

Time (hours)	0-8	9-10	11-17	18-22	23-24
Standard voltage (kV)	69	69.3	69.6	69.3	69
Upper limit (kV)	70.035	70.34	70.644	70.34	70.035
Lower limit (kV)	67.965	68.261	68.556	68.261	67.965

4.2 The Standard Range of Reactive Power Setting in a P/S

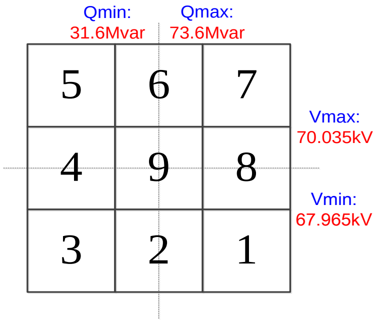
By observing Fig. 2(a) and the measurement data, the Q_{1max} is 117.3 Mvar and the Q_{1min} is 12.1 Mvar for the P/S. The reactive power is 35 Mvar for SCs. To avoid SCs will switch back in short-term, it chooses 1.2 times of the greatest variation of Q_1 as the range of reactive power (1.2*35) which is 42 Mvar. This paper assumes that the 42 Mvar is in the middle of Q_{1max} and Q_{1min}. Therefore, it sets 73.6 Mvar as the upper limit. According to the measurement data, the greatest variation of Q_1 is 42 Mvar when SCs are adjusted. Thus, the lower limit is 31.6 Mvar.



(a)

(b)

Fig. 2 The variation Q_1 of one day (a) in winter (b) in summer



5	6	7
4	9	8
3	2	1

Fig. 3 The nine-area operating range in 8:00 A.M.

By observing Fig. 2(b), the value of Q_1 is 71.215 Mvar at 8:32. If SCs switching on, the upper limit can be set. For simplifying the program, it can set the upper limit as the same value in winter. Therefore, the lower limit and the upper limit are 31.6 Mvar and 73.6 Mvar, respectively. For an instance, the nine-area operating range at 8:00 a.m. in winter and summer for the P/S is shown as Fig. 3.

4.3 The Control Strategy

The nine-area diagram may not control voltage and reactive power to the target area briefly, the situation is especially nearby the target range. If the nine-area diagram can combine with the Q-V control method, the program will be better in some states [5]. Firstly, it uses the Q-V control method to calculate the ∆V and the ∆Q after different voltage control devices operated. Secondly, it can obtain variation of all parameters by using the average value, as shown in Fig. 4.

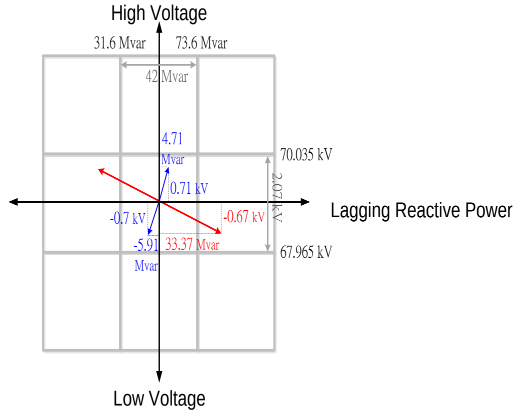


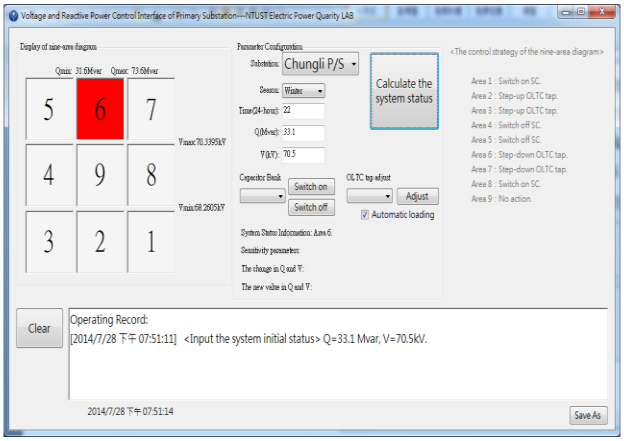
Fig. 4 The Q-V control pattern in a P/S

5. Analysis Results

In this section, there are two cases which include the analysis system by using the nine-area control strategy only and the nine-area control strategy with Q-V control method.

5.1 Analysis Results by Using the Nine-area Diagram Only

It assumes the reactive power at primary side of the main transformer (Q_1) is 33.1 Mvar, and the secondary bus voltage (V_2) is 70.5kV at 10:00 p.m. in winter in a P/S. After key in the parameters, the system status will fall in 6^{nd} area as shown in Fig. 5(a). According to the control strategy, the system status will fall in 4^{th} area when an OLTC is stepped down tap as shown in Fig. 5(b). Finally, the system status arrives to the target area after it switching off SCs as shown in Fig. 5(c). The Q-V plane is shown as Fig. 6(a).



Substation: Chungli P/S

Season: Winter

Time(24-hour): 22

Q(Mvar): 33.1

V(kV): 70.5

☑ Automatic loading

System Status Information: Area 6.

Sensitivity parameters:

The change in Q and V:

The new value in Q and V:

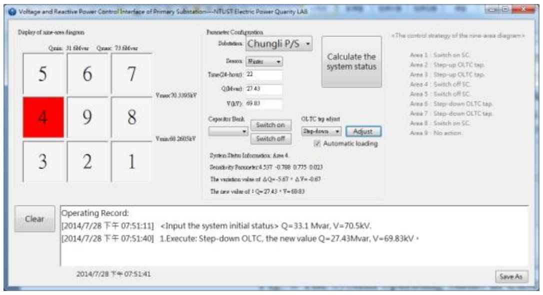
<The control strategy of the nine-area diagram>

Area 1 : Switch on SC.
Area 2 : Step-up OLTC tap.
Area 3 : Step-up OLTC tap.
Area 4 : Switch off SC.
Area 5 : Switch off SC.
Area 6 : Step-down OLTC tap.
Area 7 : Step-down OLTC tap.
Area 8 : Switch on SC.
Area 9 : No action.

```
Operating Record:
[2014/7/28 下午 07:51:11]   <Input the system initial status> Q=33.1 Mvar, V=70.5kV.
```

2014/7/28 下午 07:51:14

(a)



Voltage and Reactive Power Control Interface of Primary Substation---NTUST Electric Power Quality LAB

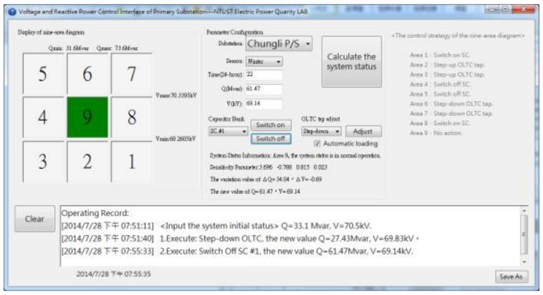
Substation: Chungli P/S
Season: Winter
Time(24-hour): 22
Q(Mvar): 27.43
V(kV): 69.83
OLTC tap adjust: Step-down
☑ Automatic loading

System Status Information: Area 4.
Sensitivity Parameter:4.537 -0.788 0.775 0.023
The variation value of ΔQ=-5.67，ΔV=-0.67
The new value of：Q=27.43，V=69.83

Operating Record:
[2014/7/28 下午 07:51:11] <Input the system initial status> Q=33.1 Mvar, V=70.5kV.
[2014/7/28 下午 07:51:40] 1.Execute: Step-down OLTC, the new value Q=27.43Mvar, V=69.83kV。

2014/7/28 下午 07:51:41

(b)



Voltage and Reactive Power Control Interface of Primary Substation---NTUST Electric Power Quality LAB

Substation: Chungli P/S
Season: Winter
Time(24-hour): 22
Q(Mvar): 61.47
V(kV): 69.14
Capacitor Bank: SC #1
OLTC tap adjust: Step-down
☑ Automatic loading

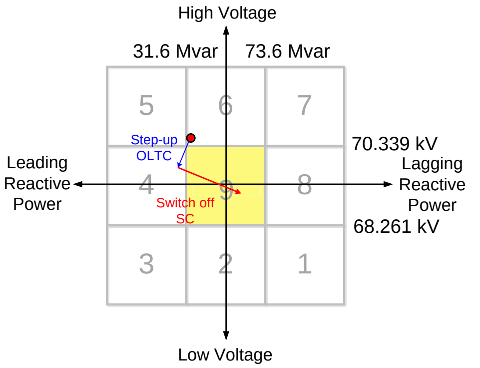
System Status Information: Area 9, the system status is in normal operation.
Sensitivity Parameter:3.696 -0.788 0.815 0.023
The variation value of ΔQ=34.04，ΔV=-0.69
The new value of Q=61.47，V=69.14

Operating Record:
[2014/7/28 下午 07:51:11] <Input the system initial status> Q=33.1 Mvar, V=70.5kV.
[2014/7/28 下午 07:51:40] 1.Execute: Step-down OLTC, the new value Q=27.43Mvar, V=69.83kV。
[2014/7/28 下午 07:55:33] 2.Execute: Switch Off SC #1, the new value Q=61.47Mvar, V=69.14kV.

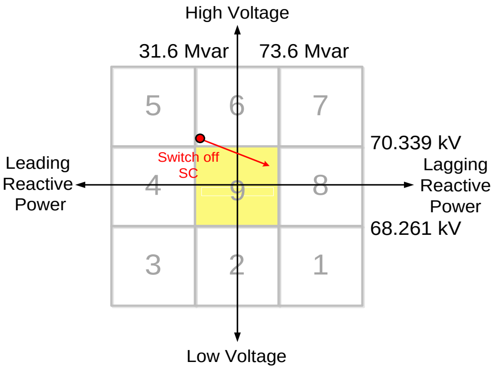
2014/7/28 下午 07:55:35

(c)

Fig. 5 The system operating status in Case1 (a) Step1, (b) Step2, (c) Step3



(a)

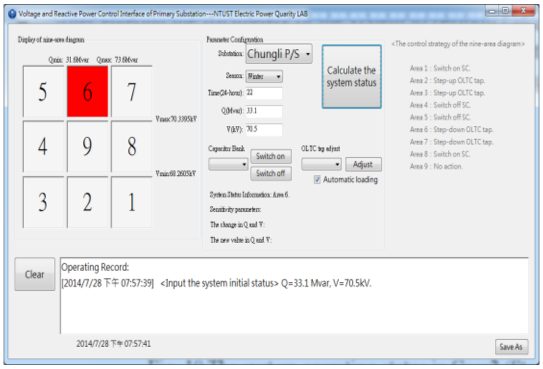


(b)

Fig. 6 The Q-V plane of (a) Case1 (b) Case2

5.2 Analysis Results by Using the Nine-area Diagram with Q-V Control Method

It assumes the initial parameters are the same as case 1. Thus, the system status will fall in 6*nd* area as shown in Fig. 7(a) after key in the parameters. The system status can arrive to the target area directly after it switching off SCs as shown in Fig. 7(b). The Q-V plane is shown as Fig. 6(b).



Voltage and Reactive Power Control Interface of Primary Substation---NTUST Electric Power Quality LAB

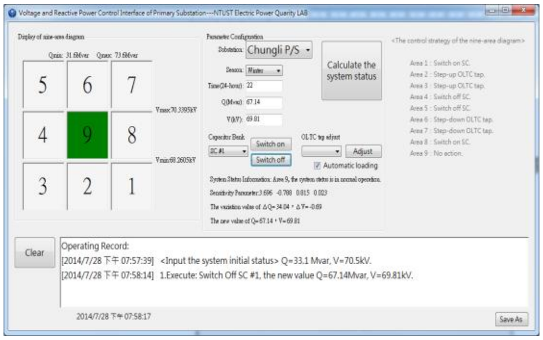
Substation: Chungli P/S
Season: Winter
Time(24-hour): 22
Q(Mvar): 33.1
V(kV): 70.5
☑ Automatic loading

System Status Information: Area 6.
Sensitivity parameters:
The change in Q and V:
The new value in Q and V:

Operating Record:
[2014/7/28 下午 07:57:39] <Input the system initial status> Q=33.1 Mvar, V=70.5kV.

2014/7/28 下午 07:57:41

(a)



Voltage and Reactive Power Control Interface of Primary Substation---NTUST Electric Power Quality LAB

Substation: Chungli P/S
Season: Winter
Time(24-hour): 22
Q(Mvar): 67.14
V(kV): 69.81
Capacitor Bank: SC #1
☑ Automatic loading

System Status Information: Area 9, the system status is in normal operation.
Sensitivity Parameter:3.696 -0.788 0.815 0.023
The variation value of ΔQ=34.04，ΔV=-0.69
The new value of Q=67.14，V=69.81

Operating Record:
[2014/7/28 下午 07:57:39] <Input the system initial status> Q=33.1 Mvar, V=70.5kV.
[2014/7/28 下午 07:58:14] 1.Execute: Switch Off SC #1, the new value Q=67.14Mvar, V=69.81kV.

2014/7/28 下午 07:58:17

(b)

Fig. 7 The system operating status in Case2 (a) Step1, (b) Step2

6. Conclusions

The system status can go back to the target area by using the nine-area diagram. It will provide the same efficacy more effectively by using the nine-area diagram with Q-V control method. The suggested method will reduce the frequency of switching on or off compensation devices, thus, it can also prolong the life of equipments.

Dispatchers key in the initial parameters can know that the system status in the Q-V plane. The nine-area diagram with Q-V control method provides a simple and effective program to dispatchers who can use the analysis results to design and determine the compensation strategies.

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