전력계통 전압 - 무효전력제어에의 최적 패턴을 이용한 내삽기법의 적용

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박영문* 이정호* 윤만철** 권태원**
* 서울대학교 전기공학과 ** 한전기술연구원

AN APPLICATION OF INTERPOLATION TECHNIQUE WITH OPTIMUM PATTERN TO VOLTAGE - REACTIVE POWER CONTROL OF POWER SYSTEM

Young-Moon Park* Jeong-Ho Lee* Man-Chul Yoon** Tae-Won Kwon**
* Seoul National University ** KEPCO Research Center

ABSTRACT

This paper introduces a new methodology to apply the interpolation technique with optimum pattern to voltage-reactive power control of power system. The conventional tool for the optimal operation of power system is Optimal Power Flow(OPF) by standard optimization techniques. The achievement of solution through OPF programs has a defect of computation time, so that it is impossible to apply the OPF programs to the real-time control area. The proposed method presents a solution in a short period of time and an output with a good accuracy. The optimum pattern is a set of input-output pairs, where an input is a load level and a type of outage and an output is the result of OPF program corresponding to the input. The output in the OPF represents control variables of voltage-reactive power control. The interpolation technique is used to obtain the solution for an arbitrary input. As a result, the new technique helps operators in the process of the real-time voltage-reactive power control in both normal and emergency operating states.

1. INTRODUCTION

The control of voltage-reactive power plays one of the most important roles in the field of modern power system operation. The main objective of this control can be generally regarded as an attempt to achieve an overall improvements of the system security, service quality and economy.

System security requires to maintain adequate voltage levels and reactive reserves in the occurrence of critical contingencies. Service quality and economy is concerned with voltage control at all buses of power system and system loss minimization. The voltage-reactive power control is focused on the operation of the installed voltage-reactive resources and control devices, i.e. the adjustment of transformer taps, switching shunt capacitors.

In the past, numerous research works have emerged to solve the control problem and many algorithms have been developed to achieve computing time requirement in real-time control. The conventional tool for the optimal operation of power system is Optimal Power Flow(OPF) by standard optimization techniques. The achievement of solution through OPF programs has a defect of computation time, so that it is impossible to apply the OPF programs to the real-time control area.

This paper shows the application of the interpolation technique with optimum pattern to voltage-reactive power control of power system to obtain a solution in a short period of time. Therefore, the proposed method is applicable to real-time control. And an output has a good accuracy, which is approximate to optimal solution.

The optimum pattern is a set of input-output pairs, where an input is a load level and a type of contingency and an output is the result of OPF program corresponding to the input. The output in the OPF represents control variables of voltage-reactive power control.

The load level at all buses of system is assumed to change in the same ratio, hence the load level as an input is a constant value. And the range of load change is divided into three intervals, i.e. off-peak, middle, and peak load level in the optimum pattern to improve the computation accuracy. Each interval in the optium pattern is composed of two load levels. Consequently, only four load levels are used to consider all the range of load change in the construction of optimum pattern. And line outage, generator outage and load outage are considered as the types of contingency.

The characteristics of interpolation technique with optimum pattern is to output the optimal solution which is the same as output of OPF for an input contained in optimum pattern and to output a solution which is approximate to optimal solution for an arbitrary input which is not in the optimum pattern.

As a result, the new technique helps operators in the process of the real-time voltage-reactive power control in both normal and emergency operating states.

2. INTERPOLATION TECHNIQUE WITH OPTIMUM PATTERN

Let n optimum patterns, i.e. input-output pairs, be given. And the pattern is represented as follows:

(x_i, y_i) for $i = 1, \cdots, n$

where

x_i is i-th $n \times 1$ input vector,

y_i is i-th $m \times 1$ output vector.

Consider linear relation between input and output.

$y = A \cdot x$

where

x is $n\times 1$ input vector,

y is $m\times 1$ output vector,

A is $m\times n$ relation matrix.

Given n optimum patterns satisfy the above linear relation.

$[\ y_1 \cdots y_n\ ] = A\cdot[\ x_1 \cdots x_n\ ]$

Hence, the relation matrix is of the form

$A = [\ y_1 \cdots y_n\ ]\cdot[\ x_1 \cdots x_n\ ]^{-1}$

The linear relation between input and output is given as

$$y=[y_1\cdots y_n]\cdot[x_1\cdots x_n]^{-1}\cdot x \tag{1}$$

The eq. (1) can be rewritten as

$$y = V\cdot W\cdot x \tag{2}$$

where

$V = [\ y_1 \cdots y_n\ ]$,

$W = [\ x_1 \cdots x_n\ ]^{-1}$.

The eq. (2) yields an output y_i in the optimum pattern when an input vector x_i in the optimum pattern is given as an input.

3. VOLTAGE-REACTIVE POWER CONTROL USING INTERPOLATION TECHNIQUE WITH OPTIMUM PATTERN

An input for voltage-reactive power control in normal operating state is load change which is represented as constant value k, since the load level at all buses of system is assumed to change in the same ratio. The output for voltage-reactive power control is tranformer tap, generator voltage, shunt capacitor.

The output vector y for a scalar input k is given by linear equation of the form

$$y = a\cdot 1 + b\cdot k = A\cdot x$$

where

$A = [\ a\ \ b\ ]$,

$x = [\ 1\ \ k\ ]^T$,

$y = [\ Q_G{}^T\ \ V_G{}^T\ \ Tap^T\ \ Q_{cap}{}^T\ ]^T$,

Q_G is reactive power generation vector,

V_G is generator voltage vector,

Tap is transformer tap vector,

Q_{cap} is shunt capacitor vector.

Assume that input-output pairs $(k_1,\ y_1)$ and $(k_2,\ y_2)$ are given.

From eq. (1) and (2),

$V = [\ y_1\ \ y_2\ ]$

$W = [\ x_1\ \ x_2\ ]^{-1}$

where

$x_i = [\ 1\ \ k_i\ ]^T$ for $i = 1,\ 2$.

The load level k which represents load change is set to 1 at all load buses for maximum load. The load levels k_1 and k_2 are used for the implementation of off-peak load level, k_2 and k_3 for middle load level and k_3 and k_4 for peak load level. The matrices V and W are constructed according to load level.

This paper discusses the control of voltage in outage cases as well as normal operating condition by way of interpolation technique with optimum pattern. The outage cases considered in this paper are line outage, generator outage and load outage.

Firstly, the formulation of interpolation technique with optimum pattern under the condition of line outage is described. The inputs considered in line outage case are load change and site of line outage. The relation between output vector y corresponding to control and inputs k for load change and Y_i for line outage is given by the equation of the form

$$y = a\cdot 1 + b\cdot k + c_1\cdot Y_1 + c_2\cdot Y_2 + \cdots + c_n\cdot Y_n + d_1\cdot k\cdot Y_1 + d_2\cdot k\cdot Y_2 + \cdots + d_n\cdot k\cdot Y_n \tag{3}$$

where

n is the number of line in power system,

$a,\ b,\ c_1,\ c_2,\ \cdots,\ c_n,\ d_1,\ d_2,\ \cdots,\ d_n$ are coefficients which are represented by matrix multiplication of V with W,

k is a scalar input for load change,

$Y_1,\ Y_2,\ \cdots,Y_n$ are inputs for line outage and have the value of 0 or 1. Y_i is equal to 1 in the case of i-th line outage, 0 in otherwise.

Eq. (3) can be rewritten as

$$y = A\cdot x$$

where

$A = [\ a\ \ b\ \ c_1\ \ c_2\ \ \cdots c_n\ \ d_1\ \ d_2 \cdots d_n\ ]$,

$x = [\ 1\ \ k\ \ Y_1\ \ Y_2\ \ \cdots Y_n\ \ k\cdot Y_1\ \ k\cdot Y_2 \cdots k\cdot Y_n\ ]^T$,

$y = [\ Q_G{}^T\ \ V_G{}^T\ \ Tap^T\ \ Q_{cap}{}^T\ ]^T$.

Assume that 2n+2 input-output pairs are given and load level is off-peak load level. Two input-output pairs (k_1,y_{11}), (k_2,y_{12}) is for normal operating condition and 2n input-output pairs (k_1,y_{21}), (k_2,y_{22}), $\cdots$,(k_1,y_{2n+1}), (k_2,y_{2n+2}) are for n single line outages.

From eq. (1) and (2),

$$V = [\ y_{11}\ \ y_{12}\ |\ y_{21}\ \ y_{22}\ |\ \cdots\ |\ y_{2n+1}\ \ y_{2n+2}\ ]$$

$$W = \left[\begin{array}{cc|cc|c|cc} 1 & 1 & 1 & 1 & & 1 & 1 \\ k_1 & k_2 & k_1 & k_2 & \cdots & k_1 & k_2 \\ \hline & & 1 & 1 & & 0 & 0 \\ & & \vdots & \vdots & \cdots & \vdots & \vdots \\ & & 0 & 0 & & 1 & 1 \\ \cline{3-7} & 0 & k_1 & k_2 & & 0 & 0 \\ & & \vdots & \vdots & \cdots & \vdots & \vdots \\ & & 0 & 0 & & k_1 & k_2 \end{array}\right]^{-1}$$

where

k_1 and k_2 are inputs for load change in optimum pattern and off-peak load level is considered by k_1 and k_2.

The matrix W can be rewritten as

$$W = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} = \left[\begin{array}{c|c} A^{-1} & -[\ I\ |\ \cdots\ |\ I\ ]D^{-1} \\ \hline 0 & D^{-1} \end{array}\right] = \left[\begin{array}{c|c} W_{11} & W_{12} \\ \hline W_{21} & W_{22} \end{array}\right]$$

where

$$W_{11} = -\frac{1}{k_1 - k_2}\begin{bmatrix} k_2 & -1 \\ -k_1 & 1 \end{bmatrix}$$

$$W_{12} = -\frac{1}{k_1 - k_2}\left[\begin{array}{cccc|cccc} -k_2 & -k_2 & \cdots & -k_2 & 1 & 1 & \cdots & 1 \\ k_1 & k_1 & \cdots & k_1 & -1 & -1 & \cdots & -1 \end{array}\right]$$

$$W_{22} = \frac{1}{k_1 - k_2}\left[\begin{array}{c|c|c|c|c|c|c|c} -k_2 & 0 & & 0 & 1 & 0 & & 0 \\ k_1 & 0 & \cdots & 0 & -1 & 0 & \cdots & 0 \\ \hline 0 & -k_2 & & 0 & 0 & 1 & & 0 \\ 0 & k_1 & \cdots & 0 & 0 & -1 & \cdots & 0 \\ \hline \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \hline 0 & 0 & & -k_2 & 0 & 0 & & 1 \\ 0 & 0 & \cdots & k_1 & 0 & 0 & \cdots & -1 \end{array}\right]$$

Similarly, matrices V and W can be constructed for middle and peak load level.

Secondly, the formulation of interpolation technique with optimum pattern under the condition of generator outage is described. The inputs considered in generator outage case are load change and site of generator outage. The relation between output vector y corresponding to control and inputs k for load change and ΔP_{Gi} for generator outage is given by the equation of the form

$$y = a\cdot 1 + b\cdot k + c_1\cdot\Delta P_{G1} + c_2\cdot\Delta P_{G2} + \cdots + c_n\cdot\Delta P_{Gn} + d_1\cdot k\cdot\Delta P_{G1} + d_2\cdot k\cdot\Delta P_{G2} + \cdots + d_n\cdot k\cdot\Delta P_{Gn} \quad (4)$$

where

n is the number of generator in power system,

ΔP_{G1}, ΔP_{G2}, $\cdots$,ΔP_{Gn} are inputs for generator outage and represent the ouatge ratio which has the value of 0 to 1. ΔP_{Gi} is equal to 1 in the case of i-th generator 100% outage, 0.5 in i-th generator 50% outage and 0 in normal condition.

Eq. (4) can be rewritten as

$$y = A\cdot x$$

where

$A = [\ a \ \ b \ \ c_1 \ \ c_2 \ \cdots \ c_n \ \ d_1 \ \ d_2 \ \cdots \ d_n\ ]$,

$x = [\ 1 \ k \ \Delta P_{G1} \ \Delta P_{G2} \cdots \Delta P_{Gn} \ k\cdot\Delta P_{G1} \ k\cdot\Delta P_{G2} \cdots k\cdot\Delta P_{Gn}\ ]^T$,

$y = [\ Q_G^T \ \ V_G^T \ \ Tap^T \ \ Q_{cap}^T\ ]^T$.

Assume that 2n+2 input-output pairs are given and load level is off-peak load level. Two input-output pairs (k_1, y_{11}), (k_2, y_{12}) is for normal operating condition and 2n input-output pairs (k_1, y_{21}), (k_2, y_{22}), $\cdots$, (k_1, y_{2n+1}), (k_2, y_{2n+2}) are for n generator outages.

The matrices V and W in generator outage case have the same structure as in line outage case.

Similarly, matrices V and W can be constructed for middle and peak load level.

Arbitrary input in the i-th generator outage case is of the form

$$x = [\ 1 \ k \ 0 \cdots 0 \ \underset{2+i}{\alpha} \ 0 \cdots 0 \ \underset{2+n+i}{\alpha\cdot k} \ 0 \cdots 0\ ]^T$$

where

α is a generator outage ratio.

Finally, the formulation of interpolation technique with optimum pattern under the condition of load outage is described. The inputs considered in load outage case are load change and site of load outage. The relation between output vector y corresponding to control and inputs k for load change and ΔP_{Li} for load outage is given by the equation of the form

$$y = a\cdot 1 + b\cdot k + c_1\cdot\Delta P_{L1} + c_2\cdot\Delta P_{L2} + \cdots + c_n\cdot\Delta P_{Ln} + d_1\cdot k\cdot\Delta P_{L1} + d_2\cdot k\cdot\Delta P_{L2} + \cdots + d_n\cdot k\cdot\Delta P_{Ln} \quad (5)$$

where

n is the number of load in power system,

ΔP_{L1}, ΔP_{L2}, $\cdots$,ΔP_{Ln} are inputs for load outage and represent the outage ratio which has the value of 0 to 1. ΔP_{Li} is equal to 1 in the case of i-th load 100% outage, 0.5 in i-th load 50% outage and 0 in normal condition.

Eq. (5) can be rewritten as

$$y = A\cdot x$$

where

$A = [\ a \ \ b \ \ c_1 \ \ c_2 \ \cdots \ c_n \ \ d_1 \ \ d_2 \ \cdots \ d_n\ ]$,

$x = [\ 1 \ k \ \Delta P_{L1} \ \Delta P_{L2} \cdots \Delta P_{Ln} \ k\cdot\Delta P_{L1} \ k\cdot\Delta P_{L2} \cdots k\cdot\Delta P_{Ln}\ ]^T$,

$y = [\ Q_G^T \ \ V_G^T \ \ Tap^T \ \ Q_{cap}^T\ ]^T$.

Assume that 2n+2 input-output pairs are given and load level is off-peak load level. Two input-output pairs (k_1, y_{11}), (k_2, y_{12}) is for normal operating condition and 2n input-output pairs (k_1, y_{21}), (k_2, y_{22}), $\cdots$, (k_1, y_{2n+1}), (k_2, y_{2n+2}) are for n load outages.

The matrices V and W in load outage case have the same structure as in line outage case.

Similarly, matrices V and W can be constructed for middle and peak load level.

Arbitrary input in the i-th load outage case is of the form

$$x = [\ 1 \ k \ 0 \cdots 0 \ \underset{2+i}{\beta} \ 0 \cdots 0 \ \underset{2+n+i}{\beta\cdot k} \ 0 \cdots 0\ ]^T$$

where

β is a load outage ratio.

4 TEST RESULTS

The proposed approach is verified by computer simulation of IEEE 14-bus network (Fig. 1). The 14-bus system has five generators, three static condensers, three transformers, and twenty transmission lines. Table 1 gives line data and tap settings. Table 2 gives limits on taps, voltages and var sources. Table 3 shows the load condition at load level, k is equal to 0.9. Table 4 gives the results of the studies on the 14-bus system at load level ,k is equal to 0.9. The load level, k is equal to 0.58 and 0.66 are used for the off-peak load level in the optimum pattern, 0.66 and 0.8 for the middle load level and 0.8 and 0.93 for the peak load level. Case 1 gives the result of normal condition in Table 4. Case 2 gives the result of line outage at bus 12 in Table 4. Case 3 gives the result of generator outage at bus 6 in Table 4. Case 4 gives the result of load outage at bus 9 in Table 4.

Table 1 Line data of the 14-bus study system on 100 MVA Base

Line No.	Between buses from	to	Line impedance R (p.u.)	X (p.u.)	Half line charging susceptance(p.u.)	tap setting
1	1	2	0.01938	0.05917	0.0264	
2	2	3	0.04699	0.19797	0.0219	
3	2	4	0.05811	0.17632	0.0187	
4	1	5	0.05403	0.22304	0.0246	
5	2	5	0.05695	0.17388	0.0170	
6	3	4	0.06701	0.17103	0.0173	
7	4	5	0.01335	0.04211	0.0064	
8	5	6	0.0	0.25202	0.0	1.000
9	4	7	0.0	0.20912	0.0	0.975
10	7	8	0.0	0.17615	0.0	
11	4	9	0.0	0.55618	0.0	0.9625
12	7	9	0.0	0.11001	0.0	
13	9	10	0.03181	0.08450	0.0	
14	6	11	0.09498	0.19890	0.0	
15	6	12	0.12291	0.25581	0.0	
16	6	13	0.06615	0.13027	0.0	
17	9	14	0.12711	0.27038	0.0	
18	10	11	0.08205	0.19207	0.0	
19	12	13	0.22902	0.19988	0.0	
20	13	14	0.17093	0.34802	0.0	

Table 2 Limits on taps, voltages and var sources

Tap	: $0.95 \le T_{56} \le 1.06$	
	$0.95 \le T_{47} \le 1.06$	
	$0.95 \le T_{49} \le 1.06$	
Voltage	: $0.95 \le V_i \le 1.05$	$i=1,\cdots,14$
Var sources:	$-15 \le Q_1 \le 50$	
	$-15 \le Q_2 \le 40$	
	$-15 \le Q_3 \le 40$	
	$-15 \le Q_6 \le 50$	
	$-15 \le Q_8 \le 50$	
	$0 \le Q_4 \le 5$	
	$0 \le Q_{10} \le 10$	
	$0 \le Q_{14} \le 5$	

Table 3. Load condition

Bus No.	Load (MW) PL	QL
1	0.000	0.000
2	19.530	11.430
3	84.780	17.100
4	43.020	-3.510
5	24.840	10.440
6	10.080	6.750
7	0.000	0.000
8	0.000	0.000
9	26.550	5.940
10	26.100	5.220
11	21.150	1.620
12	23.490	1.440
13	12.150	5.220
14	13.410	4.500

Table 4 The results of the studies on the 14-bus system

VARIABLE	CASE 1 initial	CASE 1 final	CASE 2 initial	CASE 2 final	CASE 3 initial	CASE 3 final	CASE 4 initial	CASE 4 final
VOL 1	1.000	1.033	1.000	1.036	1.010	1.036	1.000	1.036
VOL 2	1.000	1.025	1.000	1.026	1.005	1.029	1.000	1.027
VOL 3	1.000	1.017	1.000	1.019	1.000	1.020	1.000	1.023
VOL 4	0.984	1.009	0.980	1.013	0.964	1.003	0.989	1.016
VOL 5	0.986	1.009	0.981	1.010	0.961	0.995	0.990	1.017
VOL 6	1.000	1.012	1.000	1.037	0.916	0.989	1.000	1.029
VOL 7	0.990	1.011	0.995	0.997	0.971	0.998	0.997	1.028
VOL 8	1.000	1.026	1.000	1.035	1.000	1.038	1.000	1.026
VOL 9	0.979	1.005	0.931	0.999	0.951	1.000	0.992	1.029
VOL10	0.967	0.997	0.926	0.996	0.929	0.990	0.978	1.020
VOL11	0.971	0.992	0.947	1.002	0.910	0.978	0.976	1.013
VOL12	0.967	0.982	0.964	1.006	0.884	0.959	0.968	1.000
VOL13	0.976	0.993	0.968	1.013	0.899	0.972	0.978	1.012
VOL14	0.961	0.990	0.928	0.994	0.910	0.978	0.969	1.012
QG 1	-9.446	0.000	-7.633	3.862	-6.658	0.626	-3.431	0.000
QG 2	8.813	16.106	13.804	7.793	40.000	27.687	2.801	6.854
QG 3	25.570	15.434	28.010	15.150	33.559	19.853	23.092	16.878
QG 4	0.000	3.311	0.000	4.608	0.000	4.682	0.000	1.995
QG 6	24.326	20.540	35.303	25.806	0.000	0.000	21.568	31.817
QG 8	8.506	10.906	5.496	24.516	19.387	26.797	4.425	0.778
QG 10	0.000	8.464	0.000	9.188	0.000	9.348	0.000	7.437
QG 14	0.000	4.621	0.000	4.533	0.000	4.599	0.000	4.754
TAP 1	1.0	1.011	1.0	0.991	1.0	0.958	1.0	1.025
TAP 2	0.975	0.995	0.975	1.051	0.975	1.045	0.975	0.984
TAP 3	0.9625	0.991	0.9625	0.958	0.9625	0.954	0.9625	0.978

5. CONCLUSION

The interpolation technique with optimum pattern for voltage-reactive power control of power system is presented in this paper. The proposed method presents a solution in a short period of time compared to the conventional approach such as OPF and an output with a good accuracy. Thus, the presented methodology would be a particularly useful tool to assist the system operator in making control decisions in normal and emergency operating conditions.

6. REFERENCES

[1] K.R.C.Mamandur and R.D.Chenoweth, "Optimization of reactive power flow for improvements in voltage profiles and for real power loss minimization ", IEEE Trans. on Power Apparatus and Systems, Vol.PAS-100, No. 7, pp. 3185~3193, 1981.

[2] Chen-Ching Liu and Kevin Tomsovic, "An expert system assisting decision-making of reactive power/voltage control", IEEE Trans. on Power systems, Vol. PWRS-1, No. 3, pp. 195~201, 1986.

[3] Milan Bjelogrlic, Milan S. Calovic and Borivoje S. Babic, "Application of Newton's optimal power flow in voltage/reactive power control", IEEE Trans. on Power Systems, Vol. 5, No. 4, pp. 1447~1454, 1990.

[4] C.S. Chang, T.S. Chung and K.L. Lo., "Application of pattern recognition technique to power system security analysis and optimization", IEEE Trans. on Power Systems, Vol. 5, No. 3, pp. 835~841, 1990.

[5] M.A. Pai, Computer techniques in power system analysis, Tata McGraw-Hill, 1979, pp. 208~209.

[6] KEPCO, Development of program package for optimal reactive power planning, 1988.