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Coordination of Generation of Multi Machine Power Systems

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Abstract: Electrical power is not only a necessity but also a tool for the determination of the economic position and growth of nations, however, the environmental restrictions have imposed more conditions on installing new transmission lines which has led to the problem of optimal reconfiguration that must be solved in an optimum manner for the electricity power companies. FACTS device provides the possibility to control both voltages, flow of power in a power system and real power losses. This study investigates the effects of a Static VAR Compensator (SVC) on the Optimal Power Flow (OPF) of a power system. Simulation studies were carried out in MATLAB on IEEE-5 and IEEE-26 bus power system using Newton-Raphson method to validate that the SVC can effectively improve voltage profile, reduce line losses and overall cost of generating plants.

Key words: SVC, OPF, voltage profile, line losses, generation cost, environmental

INTRODUCTION

The electrical power system is always expanding both in size and in complexity all over the world. In recent years, electrical power industry has undergone several changes because of privatization nearly all over the world which has affected power system management and energy markets (Udgir *et al*., 2011). Voltage and reactive power control is very important to the security of a power system and to the economical operation. This involves regulation of both reactive power and voltage magnitude in the power system. Proper operation and control of the system might regulate the system's voltage and reduces real power losses. The combination of both reactive and real power control will reduce the total cost of generation (Immanuel and Rajan, 2013). From the power system planning viewpoint, the optimal power flow solution can provide optimal setting of the variables in a power network. For the power operation viewpoint an optimal power flow solution can give an answer for the adjustment of available controls, so that, energy demand can be met in a most economical manner whilst keeping all of the constraints imposed on the power system within bounds (Pizano-Martinez *et al*., 2010). The result of increasing the demand of electrical power is that the industry of electrical power supply is facing many transformations worldwide. This is making the existing power transmision and distribution system more complicated. To meet this ever increasing demand on electrical power, it is necessary to increase power transmission either by installing new power lines or by improving of the existing lines by installing new devices. Addition of new lines in a system can lead to a technological complexity such as environmental and economic considerations which include cost (Singh *et al*., 2012).

A new technology which is known as Flexible Alternating Current Transmission Systems (FACTS) that has been introduced to power systems for improving the performance of large electrical networks. The IEEE definition of FACTS is "power electronic based system and other static equipments which provide the control of one or more AC transmission system parameters for the enhancement of controllability and the increase of power transmission capability". FACTS devices could be used to increase the transfer capacity and improve system stability to ensure better quality of power when compared to conventional devices such as switched compensation (Mancer *et al*., 2012).

By Vishwakarma and Saxena (2013) the improvement of the limit of voltage stability for power flow between regions in a power system using a Fixed Capacitor Thyristor Controlled Reactor (FC-TCR) or SVC is addressed. The power flow results were obtained for the

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uncompensated system and then compared with those after compensation with an SVC device. The simulation results demonstrate a better power flow profile and voltage stability.

By Singh *et al.* (2012) the model of FACT devices for the study of power flow and their impact on these voltage profile of a power system was verified. The modeling was tested and analyzed on IEEE5 bus power system.

By Padmavathi *et al.* (2013) the Newton-Raphson algorithm is adopted to determine the best operating point for an SVC device to enhance security of the power system. A proposed algorithm can iteratively minimize the security index which will indicate the level of over load of the transmission lines. The results do show that system's voltage profile can be enhanced by the application of the proposed algorithm. In this study the impact of SVC on optimal power flow of a power system is studied to verify the improvement of voltage profile, reduction of line losses and cost of generation.

MATERIALS AND METHODS

Mathematical model of static VAR compensator: An SVC is a shunt connected static VAR generator or absorber the output of which can be adjusted, so as to exchange inductive or capacitive currents to maintain and control specific parameters of the electric power system (typically magnitude of bus voltage). SVC is used for voltage control in power systems (Hingorani *et al.*, 2000; Singh *et al.*, 2012). Controlling power flow in the network, under both abnormal and normal conditions of the power system can help in reduction of power flow in heavily loaded lines, reduction of power system loss which will lead to the improvement of the stability and the performance of the power system without rescheduling generation or making topological changes in the electric network (Rambabu *et al.*, 2011). Circuit shown in Fig. 1 is used for the derivation of the SVC nonlinear power equation required by Newton's method.

As shown in Fig. 2, the characteristic of an SVC can be seen by the plot of bus voltage versus reactive power or current. In Fig. 2, the Voltage V_{ref} is the terminal voltage of the SVC when it was neither generating nor absorbing reactive power. The reference voltage value could be varied between minimum and maximum limit that is V_{ref} min and V_{ref} max using control system of the SVC. The range which passes through V_{ref} is the control range on which the voltage can be varied linearly with reactive power or current (Kazemi *et al.*, 2004). On this range, reactive power is varied from inductive to capacitive. The mathematical model equations of the SVC could be written as. The current which is drawn by the SVC: reactive power injected into the bus:

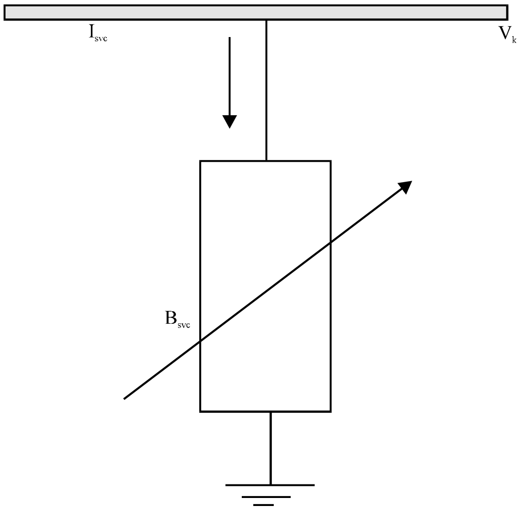

Fig. 1: Variable shunt susceptance of SVC

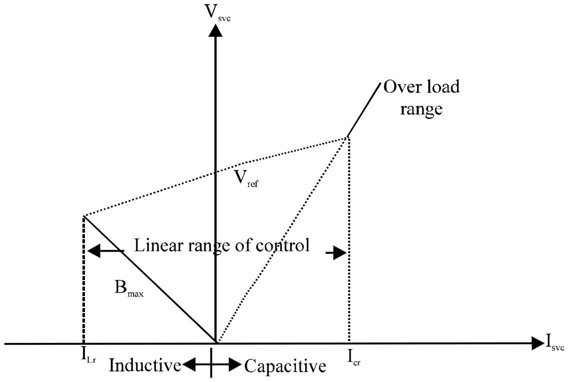

Fig. 2: V-I characteristics of SVC

$$I_{SVC} = jB_{SVC} * V_k \tag{1}$$

$$Q_{SVC} = Q_x = -V_k^2 * B_{SVC} \tag{2}$$

The linearized equation of SVC where the B_{svc} is taken as a state variable are:

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & Q_k \end{bmatrix} \begin{bmatrix} \Delta\theta_k \\ \Delta B_{SVC}/B_{SVC} \end{bmatrix} \tag{3}$$

At the end of kth iteration the value of the susceptance can be updated as:

$$B_{SVC}^{K} = B_{SVC}^{k-1} + \left(\frac{\Delta B_{SVC}}{B_{SVC}}\right)^{k} B_{SVC}^{k-1} \qquad (4)$$

The susceptance value was varied in each iteration of the Newton-Raphson load flow method as a state variable until the bus voltage magnitude to which the SVC is connected to is set to a specified value:

Optimal power flow: In an interconnected multi machine power system, the objective is to determine the real and the reactive power scheduling in each generator in such a way, so that, the operation cost is minimum. In an OPF problem, the aim is the determination of control settings, so that, a particular objective function is minimized while taking into consideration the constraints of inequality and equality according to the model at hand. The optimum settings were determined by solving the optimization problem using lagrange multipliers (Hug-Glanzmann and Andersson, 2007; Sadaat, 1988):

$$\text{Minimize } f(x) \qquad (5)$$

Subjected to:

$$g(x) = 0(6) \qquad (6)$$

$$h(x) \le 0 \qquad (7)$$

$$\Gamma = f + \sum_{i=1}^{k} \lambda_i g_i + \sum_{j=1}^{m} \mu_j h_j \qquad (8)$$

The OPF problem is to minimize of the overall generation cost:

$$F_t = \sum_{i=1}^{ng} F_i \; i = 1, ..., ng \qquad (9)$$

$$= \sum_{i=1}^{ng} \alpha_i + \beta_i P_i + \gamma_i P_i^2 \; i = 1, ..., ng \qquad (10)$$

Subjected to the equality constraint that is generation is equal to total demand plus losses:

$$\sum_{i=1}^{ng} P_i = P_D + P_L \; i = 1, ..., ng \qquad (11)$$

The inequality constraint is:

$$P_{i(min)} \le P_i \le P_{i(max)} \; i = 1, ..., ng \qquad (12)$$

Where:

λ and μ = Are the lagrange multipliers
F_i = Quadratic Function of real power generation
α_i β_i and γ_i = Coefficient of quadratic real power equation. P_i output power of generator i
P_D = Total load of Power system
P_L = Power losses
$P_{i\,(min)}$ = The minimum generating limits of generator i
$P_{i\,(min)}$ = Maximum generating limits of generator i
ng = Number of the generating units

RESULTS AND DISCUSSION

The IEEE5-bus power system (Sadaat, 1988) shown in Fig. 3 is first used to show the effectiveness of connecting the SVC on voltage profile, power losses and generation cost reduction. Load flow is first carried out using Newton-Raphson method the results are shown in Table 1. After evaluating the system for the optimal operation, the final optimal dispatch of generation was obtained in seven iterations. The results for the final loss coefficients are shown:

$$B = \begin{bmatrix} 0.0472 & 0.0130 & 0.0036 \\ 0.0130 & 0.0130 & 0.0010 \\ 0.0036 & 0.0010 & 0.0155 \end{bmatrix}$$

$$B0 = \begin{bmatrix} 0.0047 & 0.0012 & 0.0004 \end{bmatrix}$$

$$B00 = \begin{bmatrix} 3.0516e\text{-}04 \end{bmatrix}$$

Total system loss = 2.15434 MW, total generation cost = 1596.96 $/h. Total system loss which was initially 3.05248 MW is now reduced to 2.15434 MW. This is an improvement of about 0.89814 MW. The total generation of cost for the initial operating condition was 1633.24 $/h and the total generation of cost with optimal dispatch is 1596.96 $/h, this results in savings of about 36.28 $/h. That is a total annual savings of $317,812.8. The final optimal generation is shown in Table 2.

The SVC is now connected at bus-5 for it is seen as the weakest bus as far as voltage magnitude is concerned to regulate its voltage to 1.01 pu. Load flow using Newton-Raphson was carried out and the following results were obtained as in Table 3. The value for the susceptance used to achieve a voltage magnitude of 1.01 pu at bus-5 was 0.2284 pu. The final loss coefficients obtained when the optimal power flow program is carried out with the SVC connected at bus 5 are as shown:

Table 1: Load flow results of 5-bus power system without SVC connected

Newton-Raphson method

			Load		Generation	
Bus No.	Voltage mag.	Angle (°)	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1	1.060	0.000	0.00	0.00	83.051	7.271
2	1.045	-1.782	20.00	10.00	40.00	41.811
3	1.030	-2.664	20.00	15.00	30.00	24.148
4	1.019	-3.243	50.00	30.00	0.00	0.00
5	0.990	-4.405	60.00	40.00	0.00	0.00
Total			150.000	95.00	153.051	73.230

Maximum power mismatch = 1.43025e-05; No. of iterations = 3

Table 2: Optimal dispatch of generation without SVC connected

No. of generators	Power delivered (MW)
1 (slack)	23.5581
2	69.5593
3	59.0368

Table 3: Load flow results of 5-bus power system with SVC connected at bus-5

Newton-Raphson method

			Load		Generation	
'Bus No.	Voltage mag.	Angle (°)	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1	1.060	0.000	0.00	0.00	82.642	7.392
2	1.045	-1.773	20.00	10.00	40.000	23.604
3	1.030	-2.648	20.00	15.00	30.000	17.531
4	1.021	-3.259	50.00	30.00	0.000	0.000
5	1.010	-4.703	60.00	60.00	0.000	0.00
Total			150.00 0	95.000	152.642	48.527

Maximum power mismatch = 4.88801e-05; No. of iterations = 3

$$B = \begin{bmatrix} 0.0216 & 0.0088 & 0.0027 \\ 0.0088 & 0.0146 & 0.0010 \\ 0.0027 & 0.0010 & 0.0115 \end{bmatrix}$$

$$B0 = \begin{bmatrix} 0.0002 & 0.0017 & 0.0005 \end{bmatrix}$$

$$B00 = \begin{bmatrix} 3.0243\text{e-}04 \end{bmatrix}$$

- Total system loss = 1.89369 MW
- Total generation cost = 1594.11 $/h
- New value of susceptance = 0.0147

Total system loss was originally 3.05248 MW and was reduced to 2.15434 MW, however, when the SVC was connected and optimal dispatch is used the losses were reduced even more to a value of 1.89369 MW and this mainly due to a better voltage profile which is clearly apparent when a comparison between voltage magnitudes in Table 1 and 3 is made. The final or optimal generation is shown in Table 4 and Fig. 3.

The total generation cost for the initial operating condition was 1633.24 $/h while the total generation cost with optimal dispatch and SVC connected at bus-5 is 1594.11$/h. This is a saving of 39.13 $/h. It's is more than

Table 4: Optimal dispatch of generation without SVC connected

No. of generators	Power delivered (MW)
1 (slack)	30.3689
2	66.0420
3	55.4827

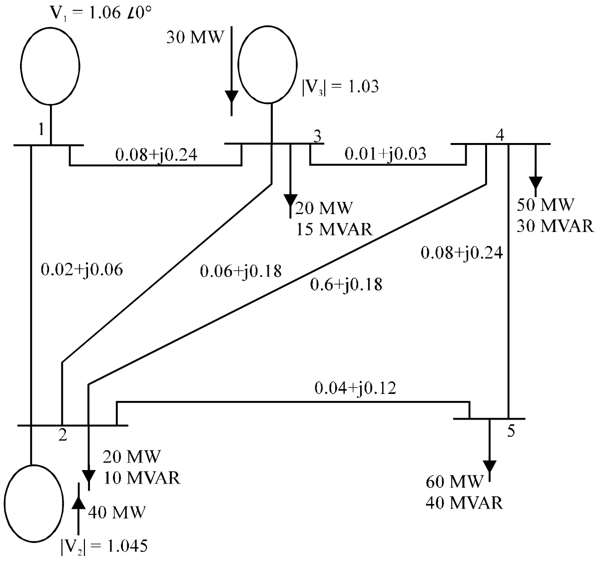

Fig. 3: One line diagram of IEEE-5 power system

Table 5: Load flow results of 26-bus power system without SVC connected

Newton-Raphson method

			Load		Generation	
Bus No.	Voltage mag.	Angle (°)	P (MW)	Q (MVAR)	P (MW)	Q(MVAR)
1	1.025	0.000	51.00	41.00	719.534	224.011
2	1.020	-0.931	22.00	15.00	79.000	125.354
3	1.035	-4.213	64.00	50.00	20.000	63.030
4	1.050	-3.582	25.00	10.00	100.000	49.223
5	1.045	1.129	50.00	30.00	300.000	124.466
6	0.999	-2.573	76.00	29.00	0.00	0.00
7	0.994	-3.204	0.00	0.00	0.00	0.00
8	0.997	-3.299	0.00	0.00	0.00	0.00
9	1.009	-5.393	89.00	50.00	0.00	0.00
10	0.989	-5.561	0.00	0.00	0.00	0.00
11	0.997	-3.218	25.00	15.00	0.00	0.00
12	0.993	-4.692	89.00	48.00	0.00	0.00
13	1.014	-4.430	31.00	15.00	0.00	0.00
14	1.000	-5.040	24.00	12.00	0.00	0.00
15	0.991	-5.538	70.00	31.00	0.00	0.00
16	0.983	-5.882	55.00	27.00	0.00	0.00
17	0.987	-4.985	78.00	38.00	0.00	0.00
18	1.007	-1.866	153.00	67.00	0.00	0.00
19	1.004	-6.397	75.00	15.00	0.00	0.00
20	0.980	-6.025	48.00	27.00	0.00	0.00
21	0.977	-5.778	46.00	23.00	0.00	0.00
22	0.978	-6.437	45.00	22.00	0.00	0.00
23	0.976	-7.087	25.00	12.00	0.00	0.00
24	**0.968**	-7.347	54.00	27.00	0.00	0.00
25	0.974	-6.775	28.00	13.00	0.00	0.00
26	1.015	-1.803	40.00	20.00	60.00	32.706
Total			1263.00	637.00	1278.534	618.791

Maximum power mismatch = 3.18289e-010; No. of iterations = 6

$$B = \begin{bmatrix} 0.0017 & 0.0012 & 0.0007 & -0.0001 & -0.0005 & -0.0002 \\ 0.0012 & 0.0014 & 0.0009 & 0.0001 & -0.0006 & -0.0001 \\ 0.00017 & 0.0009 & 0.0031 & 0.0000 & -0.0010 & -0.0006 \\ -0.0001 & 0.0001 & 0.0000 & 0.0024 & -0.0006 & -0.0008 \\ -0.0005 & -0.0006 & -0.0010 & -0.0006 & 0.0129 & -0.0002 \\ -0.0002 & -0.0001 & -0.0006 & -0.0008 & -0.0002 & 0.0150 \end{bmatrix}$$

$$B0 = \left[1.0e\text{-}03^{*}\,(-0.3908 \;\; -0.1297 \;\; 0.7047 \;\; 0.0591 \;\; 0.2162 \;\; -0.6635)\right]$$

$$B00 = \left[0.0056\right]$$

that of the base case which was 36.28 $/h where no SVC was connected, therefore, a new saving of 2.85 $/h is achieved. The other system to be used is the IEEE-26 bus power system (Sadaat, 1998) to show the improvements of connecting the SVC is shown in Fig. 4. Load flow is first carried out using Newton-Raphson method the results are shown in Table 5. The final optimal dispatch of generation was obtained in three iterations. The results for the final loss coefficients are shown:

- Total system loss = 12.8004 MW
- Total generation cost = 15447.72 $/h

Table 6: Optimal dispatch of generation without SVC connected

No. of generators	Power delivered (MW)
1 (slack)	447.692
2	173.194
3	263.486
4	138.814
5	165.588
6	87.026

Total system loss which was initially 15.53 MW is reduced to 12.8004 MW. This is an improvement of about 2.73 MW. The total generation of cost for the initial operating condition was 16760.73 $/h while the total generation of cost with optimal dispatch is 15447.72 $/h, this results in savings of about 1, 313.01 $/h. That is a total annual savings of more than $11 million. The final optimal dispatch of generation is shown in Table 6.

$$B = \begin{bmatrix} 0.0016 & 0.0010 & 0.0007 & -0.0001 & -0.0005 & -0.0002 \\ 0.0010 & 0.0012 & 0.0008 & 0.0001 & 0.0004 & -0.0001 \\ 0.0007 & 0.0008 & 0.0033 & 0.0000 & -0.0011 & -0.0006 \\ -0.0001 & 0.0001 & 0.0000 & 0.0025 & -0.0006 & -0.0008 \\ -0.0005 & -0.0004 & -0.0011 & -0.0006 & 0.0116 & -0.0002 \\ -0.0002 & -0.0001 & -0.0006 & -0.0008 & -0.0002 & 0.0146 \end{bmatrix}$$

$$B0 = [1.0e\text{-}003 * (-0.3650 \quad 0.0415 \quad 0.9412 \quad 0.0642 \quad 0.1892 \quad -0.5847)]$$

$$B00 = [0.0056]$$

Table 7: Load flow results of 26-bus power system with SVC connected at bus-24

Newton-Raphson method

			Load		Generation	
Bus No.	Voltage mag.	Angle (°)	P (MW)	Q (MVAR)	P (MW)	Q (MVAR)
1	1.025	0.000	51.00	41.00	719.094	213.504
2	1.020	-0.928	22.00	15.00	79.000	116.979
3	1.035	-4.191	64.00	50.00	20.000	55.189
4	1.050	-3.581	25.00	10.00	100.000	30.782
5	1.045	1.114	50.00	30.00	300.000	114.378
6	1.002	-2.615	76.00	29.00	0.000	0.000
7	0.996	-3.219	0.00	0.00	0.000	0.000
8	0.998	-3.306	0.00	0.00	0.000	0.000
9	1.012	-5.402	89.00	50.00	0.000	0.000
10	0.994	-5.577	0.00	0.00	0.000	0.000
11	1.000	-3.238	25.00	15.00	0.000	0.000
12	0.995	-4.694	89.00	48.00	0.000	0.000
13	1.014	-4.410	31.00	15.00	0.000	0.000
14	1.001	-5.021	24.00	12.00	0.000	0.000
15	0.993	-5.519	70.00	31.00	0.000	0.000
16	0.986	-5.872	55.00	27.00	0.000	0.000
17	0.990	-4.964	78.00	38.00	0.000	0.000
18	1.008	-1.876	153.00	67.00	0.000	0.000
19	1.015	-6.469	75.00	15.00	0.000	0.000
20	0.987	-6.051	48.00	27.00	0.000	0.000
21	0.988	-5.860	46.00	23.00	0.000	0.000
22	0.988	-6.504	45.00	22.00	0.000	0.000
23	0.987	-7.143	25.00	12.00	0.000	0.000
24	**1.000**	-7.741	54.00	27.00	0.000	0.000
25	0.983	-6.796	28.00	13.00	0.000	0.000
26	1.015	-1.800	40.00	20.00	60.000	29.951
Total			1263.00	637.00	1278.094	560.783

Maximum power mismatch = 3.13116e-010; No. of iterations = 6

The SVC is now connected at bus-24 as it is realized as the weakest bus as far as voltage magnitude is concerned, to regulate its voltage magnitude at 1 pu. Load flow using Newton-Raphson method was carried out and the following results were obtained as shown in Table 7.

The value for the susceptance used to achieve a voltage magnitude of 1pu at bus-24 was -0.0008 pu. The final loss coefficients obtained when the optimal power flow program is carried out with the SVC connected at bus 24 are as shown.

- Total system loss = 12.1688 MW
- Total generation cost = 15438.99 $/h

The total generation cost for the initial operating condition was 16760.73 $/h while the total generation cost with optimal dispatch and SVC connected at bus 24 is 15438.99 $/h. This is a saving of 1, 321.74 $/h. It's is more than the base case which was 1, 313.01 $/h when the SVC was not connected, therefore, new savings of 8.73 $/h have been earned. The total system loss was originally 15.5340 MW which was reduced to 12.8004 MW when the optimal dispatch of generation was used, however, when the SVC was connected, the losses were reduced even more to a value of 12.1688 MW and this mainly due to a better voltage profile which is clearly apparent when a comparison between voltage magnitudes in Table 5 and 7 is made (Fig. 4).

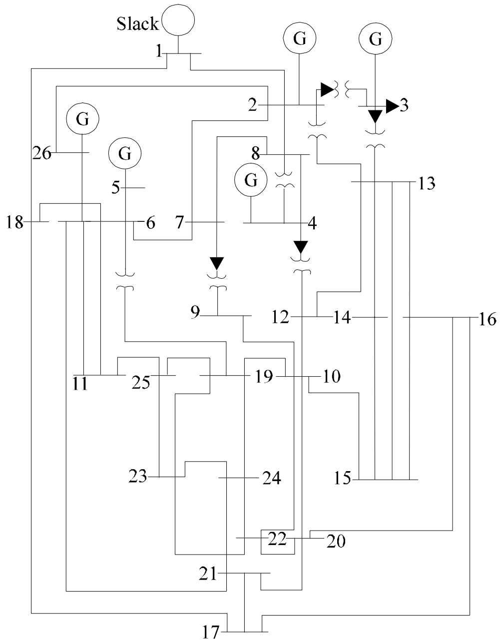

Fig. 4: One line diagram of IEEE-26-bus power system without SVC connected

CONCLUSION

The model for the power system including the SVC was successfully carried out and investigated to verify the improvement in power system performance. The results when the SVC was connected were compared with those when it was not connected. It was shown that the overall cost, transmission losses were indeed reduced and a better voltage profile was achieved.

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