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# REACTIVE POWER COMPENSATION IN DISTRIBUTION SYSTEMS OF MINING COMPANIES

Major mining sector power consumers use both active and reactive power to create network flows. Reactive power compensation and the effective placement of compensating devices is a top priority in view of energy efficiency policies. Power compensation is a priority issue when optimizing voltage modes and power consumption in order to reduce active losses and improve energy quality. An effective solution which could help reduce power network losses is the installation of reactive power compensating devices (RPC). Analysis of optimum power calculation methods and determination of the location of compensating devices takes into account the specific operating conditions of mining companies, namely, the necessity to separate power networks into surface and underground networks. The target function has been represented based on annual reduced cost data and a system of limitations for the target function has been determined. The target function analysis shows that the function is separable, and the task could be solved with discrete programming methods.

***Keywords:*** mining companies, reactive power, compensation, target function, limits, cost function, minimization, discrete programming, equivalent characteristics.

Mining companies, in particular mining and processing integrated works, feature large installed capacity, a complex and divergent power network structure, specific operation modes as well as specific modes for interacting with power systems. In this respect, RPC and determining effective locations for compensating devices is a top priority for mining companies in view of energy efficiency policies. Power compensation is a priority issue when optimizing voltage modes and power consumption in order to reduce active losses and improve energy quality. An effective solution which could help reduce power network losses is the installation of RCP devices [1]. Effective power consumption becomes even more important when switching to energy efficiency technology and taking into account ever-growing power prices.

Analysis of existing optimum power calculation methods and the location of compensating devices (CD) shows that the discrete programming method is the most effective solution for mining companies to optimize reactive load compensation (RLC). This solution helps create an RCP model accounting for the specifics of mining companies' power networks (separated into surface and underground networks) and obtain simple and effective problem solution algorithms [2, 4].

The nominal power of compensating devices $Q_{ki}$ (for power networks up to 1 kW and more than 1 kW) and reactive power generated by synchronous motors (SM) can be determined with a target function based on minimum reduced cost:

$$C = \sum_{1}^{N} C_{ki}\left(Q_{ki}\right) + C_E \qquad (1)$$

where $C_{ki}\left(Q_{ki}\right)$ is capital cost for CD installation, capacity is $Q_{ki}$; $N$ is SM and CD number; $C_E$ is the function of the cost of reactive power compensation.

Cost function $C_E$ can be presented as follows

$$C_E = c_0 \Delta P_P = \frac{c_0}{U^2}\left\|\bar{Q} - \bar{Q}_k\right\| R \left\|\bar{Q} - Q_k\right\|,$$

where $c_0$ is the unit cost of power and energy loss reduced to the active power cost; $\Delta P_P$ is active power loss; $U$ – system voltage; $\bar{Q}$ – vector maximum designed reactive loads of network nodes; $\bar{Q}_k$ – vector of CD power; $R$ – matrix of node active network (6−10 kW) resistance with respect to the main step-down substation (MSS).

The target function (1) is determined with specific limitations:

$$\sum_{1}^{N} Q_{ki} = Q_k,\ Q_{k\min i} \le Q_{ki} \le Q_{k\max i}\ \ i = 1, 2, \ldots, N,$$

$$Q_{ki} \in \{Q_{kн}\}\ \ i = 1, 2, \ldots, n,$$

where $Q_k$ is the necessary total power of synchronous compensating devices in the installed power system; $\{Q_{kн}\}$ is the variety of standard CD power values; $n$ is the CD number.

The function of the cost of compensating devices $C_{ki}(Q_{ki})$, due to specific operation principles of underground and surface networks, shall be provided separately for networks up to 1 kV and over 1 kV:

- load bus $i$ up to 1 kV:

$$C_{ki}(Q_{ki}) = e\left[C_{LVB}(Q_{ki}) + C_{TSi}(Q_{ki}) + c_0\rho_l Q_{ki}\right];$$

- load bus $i$ up to 6–10 kV:

$$C_{ki}(Q_{ki}) = eC_{HVB}(Q_{ki}) + c_0\rho_h Q_{ki};$$

where $e$ is the annual deduction from capital costs, including standard coefficient; $C_{LVB}(Q_{ki})$ is cost for low-voltage battery; $C_{HVB}(Q_{ki})$ is cost for high-voltage battery; $C_{TSi}(Q_{ki})$ is the reduction of cost for transformer sub-station (TS) *after* installation of CD up to 1 kV $Q_{ki}$; $\rho_l$, $\rho_h$ – specific loss of active power in CD up and over 1 kV.

Cost of CD up to and over 1 kV can be determined as follows:

$$C_{CBi}(Q_{ki}) = A_i K'_{0i} + \sum_{j=1}^{A_i} B_{ij} K_{0i} + k_{\text{un}i} Q_{ki},$$

where $C_{CBi}$ is cost for condenser battery; $A_i$, $B_{ij}$ is the number of TS and the number of CD in every TS; $K'_{0i}, K_{0i}$ is the cost of switching and control equipment for one TS and one CD respectively; $k_{\text{un}i}$ is CD unit cost.

Power is supplied to mining company process sites through one- and two-transformer circuits, depending on consumer reliability category. Therefore, installation of CD on the low-voltage side of distribution transformers may result in a reduction of TS power (but this will not result in a reduction in TS quantity) by standard power stage. Then

$$C_{TSi}(Q_{ki}) = \begin{cases} C_{TS}(S'_{\text{nom}i}) - C_{TS}(S_{\text{nom}i}) \\ \qquad \text{when} \quad Q_{kmi} \le Q_{ki} \le Q_{kni}, \\ 0 \qquad \text{when} \quad Q_{ki} \le Q_{kmi} \text{ or } Q_{ki} > Q_{kmi}, \end{cases}$$

where $S'_{\text{nom}i}$ is TS nominal power ($S'_{\text{nom}i}$) which is one stage below the installed power of TS $i$ ($S_{\text{nom}i}$); $C_{TS}(S_{\text{nom}i})$, $C_{TS}(S'_{\text{nom}i})$ – TS cost, capacity is $S_{\text{nom}i}$ and $S'_{\text{nom}i}$.

Maximum and minimum CD power (the range available for a decrease of CD installed power) can be determined by the following formula:

$$Q_{k\min i} = Q_i - \sqrt{(S'_{\text{nom}i})^2 - P_i^2};$$

$$Q_{k\max i} = Q_i + \sqrt{(S'_{\text{nom}i})^2 - P_i^2}.$$

Cost function $C_{ki}(Q_{ki})$ for same type CDs can be determined by the following formula

$$C_{ki}(Q_{ki}) = eK_p m + \left[\frac{M_{1i}}{Q_{\text{nom}i}} Q_{ki} + \frac{M_{2i}}{mQ_{\text{nom}i}^2} Q_{ki}^2\right] c_0,$$

where $K_p$ is an SM exciting regulator; $m = N - n$ is the number of SM in a group; $M_{1i}$, $M_{2i}$ are constant values determined by the motor nominal parameters [3].

The active power loss can be presented as follows

$$\Delta P_{\text{M}} = \Delta P_0 + \sum_{1}^{N-1}\left(a_i Q_{ki}^2 + b_i Q_{ki}\right) + \frac{2}{U^2}\sum_{i=1}^{N-1} Q_{ki} \sum_{j=i+1}^{N} a_{kj} b_{ij}, \qquad (2)$$

where $\Delta P_0 = \frac{1}{U^2}\bar{Q}RQ$; $a_i$ and $b_i$ are coefficients related to CD installation and mounting: $a_i = \frac{1}{U^2}R_i$; $b_i = -\frac{2}{U^2}\bar{Q}R_i$ at $i = 1, 2, \ldots, N$;

$$\sum_{1}^{N} R_i = \begin{vmatrix} R_{1i} \\ R_{2i} \\ \vdots \\ R_{Ni} \end{vmatrix} - i \text{ column of matrix } N.$$

If quadratic function $i$ (in brackets) is referred to the CD cost in $i$ load bus $C_{ki}(Q_{ki})$, then the cost function C can be presented by the following formula

$$C = c_0 \Delta P_0 + \sum_{i=1}^{N} C_i(Q_{ki}) + \frac{2c_0}{U^2} \sum_{i=1}^{N-1} Q_{ki} \sum_{j=i+1}^{N} Q_{kj} R_{ij}, \quad (3)$$

where $C_i(Q_{ki}) = C_{ki}(Q_{ki}) + c_0 a_i Q_{ki}^2 + c_0 b_i Q_{ki}$ is the cost function of load bus $i$ or the cost of installation in bus $i$ of CD with power capacity $Q_{ki}$.

Analysis of target function (5) shows if $R_{ij} = 0$ for all $j = 1, 2, ..., N-1$ and $j = i+1, i+2, ..., N$, the function is separable, i.e.

$$C = c_0 \Delta P_0 + \sum_{i=1}^{N} C_i(Q_{ki}) \text{ when } \sum_{i=1}^{N} Q_{ki} = Q_k, \quad (4)$$

and the problem can be easily solved with discrete programming (DP) methods [5, 6].

However, only radial networks meet the $R_{ij} = 0$ conditions, and this limits the use of DP algorithms for an arbitrary open-loop network.

The non-separability of the RLC target function can be overcome by multiple refinement of network power consumption mode during calculation and determination of additional power losses from two varying loads at common circuit branches. However, such multiple refinement of power modes can be avoided by reducing the target function (7) to a deterministic format.

Let us accept that the bus numeration starts from the end of the main line and take into account the bus resistance matrix properties, then we can get the following final sum of the target function (6)

$$\frac{2c_0}{U^2} \sum_{i=1}^{N-1} Q_{ki} \sum_{j=i+1}^{N} Q_{kj} R_{ij} = \frac{2c_0}{U^2} \Big[ Q_{k1} Q_{k2} R_2 + $$

$$+ (Q_{k1} + Q_{k2}) Q_{k3} R_3 + \ldots + \left( \sum_{i=1}^{N-1} Q_{ki} \right) Q_{kN} R_N \Big],$$

where $R_2 = R_{12}$, $R_3 = R_{13} = R_{23}$, …, $R_N = R_{1N} = R_{2N} = \ldots = R_{N-1,N}$.

Let's denote the total power of CD in $i$ load bus by $Q_k^i = \sum_{j=1}^{i} Q_{ki}$, then the expression (6) will take on the following form

$$C = \sum_{i=1}^{N} \left[ C_i(Q_{k1}) + \frac{2c_0 R_i}{U^2} Q_k^{i-1} Q_{ki} \right]. \quad (5)$$

To simplify the calculation process, the expression (5), taking into account that $Q_{ki} = Q_k^i - Q_k^{i-1}$, can be presented as follows

$$C = \sum_{i=1}^{N} \Big[ C_i\left(Q_k^i - Q_k^{i-1}\right) +$$

$$+ \frac{2c_0}{U^2} R_1 Q_k^{i-1} \left(Q_k^i - Q_k^{i-1}\right) \Big] \quad (10)$$

with limitations:

$$Q_k^0 = 0, \quad Q_k^N = Q_k,$$

$$Q_{k\min}^{i-1} \le Q_k^{i-1} \le Q_{k\max}^{i-1},$$

$$Q_{k\min}^{i} \le Q_k^{i} \le Q_{k\max}^{i}.$$

The calculation procedure is reduced to the determination of the absolute minimum value for $C^*$ for the variables $Q_k^i$, $Q_k^j$, $Q_k^r$ with fixed set variable $Q_k = \left(Q_k^i, Q_k^j, Q_k^r\right)$ on which function $C$ depends.

By selecting $Q_k^{N-1}$ as the total power $N-1$ CD and making this value fixed, we can set it to minimum for other variables $Q_k^1$, $Q_k^2$, $Q_k^{N-2}$.

Once all calculation procedures are completed, the function minimum can be presented in the following form

$$C^* = \min \Big\{ C_N\left(Q_k^N - Q_k^{N-1}\right) +$$

$$+ \frac{2c_0}{U^2} R_N Q_k^{N-1} \left(Q_k^N - Q_k^{N-1}\right) + C_{N-1}^E\left(Q_k^{N-1}\right) \Big\},$$

where $Q_k^{N-1}$ may take on discrete values from $Q_{k\min}^{N-1}$ to $Q_{k\max}^{N-1}$, and

$$C_{N-1}^E\left(Q_k^{N-1}\right) = \sum_{i=1}^{N-1} \Big[ C_i\left(Q_k^i - Q_k^{i-1}\right) +$$

$$+ \frac{2c_0}{U^2} R_i Q_k^{i-1} \left(Q_k^i - Q_k^{i-1}\right) \Big]$$

This function can be equivalent depending on $Q_k^E$:

$$C_{N-1}^E\left(Q_k^E\right)=\min\left\{C_{N-1}\left(Q_k^E-Q_k^{N-2}\right)+\right.$$
$$+\frac{2c_0}{U^2}R_{N-1}Q_k^{N-2}\left(Q_k^E-Q_k^{N-2}\right)+$$
$$\left.+\sum_{i-1}^{N-2}\left[C_i\left(Q_k^i-Q_k^{i-1}\right)+\frac{2c_0}{U^2}R_iQ_k^{i-1}\left(Q_k^i-Q_k^{i-1}\right)\right]\right\}$$

A similar approach is used to obtain the function $C_{N-2}^E\left(Q_k^{N-2}\right)$, etc. This process continues until the following expression is obtained at the final stage

$$C_1^E\left(Q_k^E\right)=C_1\left(Q_k^1\right),$$

where $Q_{k\min}^1 \le Q_k^E = Q_k^1 \le Q_{k\max}^1$; $C_1\left(Q_k^1\right)$ is the cost function for load bus 1.

Minimization is carried out for every fixed value $Q_k^E$ from the range $\left[Q_{k\min}^i;Q_{k\max}^i\right]$ by resetting power values $Q_k^{i-1}$ that meet the requirement $Q_{k\min}^{i-1}\le Q_k^{i-1}\le Q_{k\max}^{i-1}$. The variables $Q_k^{i-1}$ take on discrete values with the pre-set quantization step $h$.

The equivalent cost characteristic $C_1^E\left(Q_k^E\right)$ determines the minimum cost for the main power line with optimum installation of reactive power sources in load buses $i$ with total power of $Q_k^E$ .

Development of equivalent characteristic $C_i^E\left(Q_k^E\right)$ means the replacement of load buses $i$, each with reactive power source (RPS) $Q_k^{i-1}$, by equivalent load bus with RPS power of $Q_k^Э=Q_k^i=\sum_{j=1}^{i}Q_{kj}$, the cost function of which is determined by the equivalent characteristic $C_i^E\left(Q_k^E\right)$.

The calculation shall start from the main line end ($i=1,2,3,\ldots,N$) and continue until all main line load buses are reduced into one load bus and optimum cost $C_N^E\left(Q_k\right)=C^*$ is determined.

**Conclusion.** The discrete programming approach for determining the effective location of compensation devices in distributing networks of mining companies has been proposed. This method helps determine the optimum solution by applying specific limitations and rules on the target function.

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