REACTIVE POWER MANAGEMENT IN ELECTRIC POWER SYSTEMS A CASE STUDY: EELPA'S SYSTEM

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ABSTRACT

The reactive power consumption by industrial plants and generation patterns in the Ethiopian Electric Light and Power Authority's (EELPA) system is critically evaluated. The flaws in the incentive mechanism for reactive power compensation are identified and recommendations made.

Further, the voltage profile at the transmission level for peak and minimum loading conditions are calculated using a load flow program, the reasons for the less than satisfactory voltage stability are discussed and recommendations made.

INTRODUCTION

The quality of electric power at a supply point can be quantified in terms of how stable are the voltage and frequency and how close is the power factor to unity. The continuity of supply and in three-phase systems the degree to which the phase currents and voltages are balanced constitute additional quality parameters.

Most industrial loads absorb reactive power. The load current, therefore, tends to be larger than the useful current in energy conversion, and, as a result, the excess current represents a waste to the consumer as well as to the supplier in the sense that it causes power loss, necessitates additional cable capacity and causes excess voltage drop. The most obvious way to counter these unfavorable effects of the reactive power would be to increase the size and number of generating units and distribution networks. However, it is much more economical and practical to size the components of the power system according to the maximum demand for real power and to manage the reactive power by means of equipment specifically designed to generate the reactive power required by the loads. On the other hand, the reduction of the load during certain parts of the daily load cycle causes a gradual voltage rise. The line charging current in long distance transmission systems causes the voltage to rise. This overvoltage (Ferranti effect) would limit the power transfer and the transmission range in the absence of any compensation measures.

In this paper, the management of the reactive power is explored with the aim of improving the quality and the reliability of the supply in the EELPA's interconnected system as well as the demand side management will be discussed and areas most amenable to improvement identified.

BRIEF REVIEW OF BASIC RELATIONS

a) Voltage Drop and Losses

For a simplified analysis, the transmission line can be modeled using a reactance connected in series with a resistance.

$$Z_s = R_s + jX_s$$

where Z_s, R_s and X_s are the line impedance, resistance and reactance, respectively.

If the line supplies the power $S = P_l + jQ_l$, where P_l and Q_l are the real and reactive power, respectively, and the voltage magnitudes at the sending- and receiving-ends of the line are E and V, respectively, then the voltage drop can be calculated using the following expression.

$$\Delta V = [(R_s P_l + X_s Q_l) + j(X_s P_l - R_s Q_l)]/V \qquad (1)$$

By adding a compensator in parallel with the load, it is possible to make $|E| = |V|$. For this special case

$$E^2 = \left(V + \frac{R_s P_l + X_s Q_s}{V}\right)^2 + \left(\frac{X_s P_l - R_s Q_s}{V}\right)^2$$

where $Q_s = Q_l + Q_c$ is valid.

Q_c is the output of the compensator

There is always a solution for Q_s whatever the value of P_l. This leads to the conclusion that a purely reactive compensator can always eliminate supply voltage variations, if it can be smoothly controlled.

If the compensator is designed in a such a way that the power factor at the supply point is unity, Eq. (1) simplifies to

$$\Delta V = (R_s + jX_s) P/V.$$

This equation shows that except for the practically unimportant case of $P_l = 0$, the compensator cannot maintain both constant voltage and unity power factor at the same time.

The total loss on the transmission line is

$$P_{loss} = R(P_l^2 + Q_l^2)/V^2 \tag{2}$$

and the loss due only to the reactive load is

$$Pq_{loss} = Rq_l^2/V^2 \tag{3}$$

Up to now, the reactive load Q_l was assumed concentrated at the end of the line. In practice, neither the distribution of the active load nor that of the reactive load in distribution feeders is known exactly, and appropriate models need to be used.

b) Voltage Profile of a Lightly Loaded Line

The fundamental equation governing the propagation of energy along a transmission line is

$d^2V/dx^2 = \Gamma^2 V,$
with $\Gamma^2 = (r+j\omega l)(g+j\omega c)$ and $\Gamma = \alpha + j\beta$.

r, l, g, and c are the resistance, inductance, conductance, and capacitance of the line per unit length. α and β are defined as the attenuation and the propagation constants of the line, respectively. For simplified analysis, the line can be assumed lossless, i.e., the attenuation constant (α) can be set equal to zero.

The solution of the transmission line wave equation is

$$V(x) = V_r \cos\beta(a-x) + jZ_0 I_r \sin\beta(a-x)$$

with a= the length and Z_0 = the wave impedance of the line. V_r and I_r are the voltage and current at the receiving end of the line, respectively. The uncompensated line at no load is characterized by $I_r = 0$. It follows that the voltage at the sending end of the line is

$$V(x=0) = E = V_r \cos\vartheta, \text{ with } \vartheta = \beta a.$$

The voltage at any arbitrary point along the line in terms of the sending-end voltage then becomes

$$V(x) = E \cos\beta(a-x)/\cos\vartheta. \tag{4}$$

An example on this point is probably instructive. Assuming c=0.012x10^{-6}F/km and l= 9.78x10^{-4} H/km which are values within the normal range for an overhead transmission line and setting E=1 p.u., the voltage at the receiving end of a 640 km long line in the absence of any compensation measures would be 1.58 p.u which clearly is a dangerously high value.

REACTIVE POWER CONSUMPTION OF SELECTED LOAD CENTERS IN THE INTERCONNECTED SYSTEM

Load compensation is the practice of generating reactive power as close as possible to the load which requires it. This is done in most cases by the industrial and large commercial consumers themselves. Utility companies charge for both the active and reactive energy (varh) to encourage consumers to operate at high power factors. The power factor tariff or penalty is imposed when a consumer operates below a specified minimum, which is 0.85 in the EELPA's case.

A survey was conducted to find out how some of the industrial consumers adhere to this requirement.

Addis Ababa

For this study, the Debre Zeit Road, due to its high density of industrial plants, was chosen. The factories selected for this study were Addis Tyre Factory, Ethiopian Rubber and Canvas Shoe Factory, ECAFCO, and Adey Ababa Yarn Factory.

All, except Adey Ababa Yarn Factory, remained, by and large, within the maximum permissible reactive power consumption, and power factor penalty was rather an exception. Within the Adey Ababa Yarn Factory, the Spin Mill No. 1 had the largest reactive power consumption. EELPA's billing register for the period from April, 1991 to March, 1994 indicates an average power factor of 0.56 with an average real power consumption of 150 kW. The factory paid on average a penalty of 850 birr per month. To raise the average power factor to the minimum required, a capacitor bank with a minimum capacity of 130 kvar is required. With the estimated cost US $3355 for the bank, the factory would save 604 birr per month if it installed one.

Bahr Dar

A study commissioned by EELPA[6] found out that the average power factor of the Bahr Dar Textile Factory during the study period was 0.75 to 0.8. Four of the existing transformers are already compensated, and the fifth, a 2500 KVA transformer, was also to be compensated using a 200 kvar switched-type bank. As a result, the factory is likely to minimize the reactive "energy" charges.

EELPA's billing register indicates a power factor of 0.88 for the biggest oil mill in town. Most of the smaller oil mills have an average power factor of 0.69. However, the mills are so small that individual compensation at the present penalty tariff is not economically justifiable for the plants.

Nazreth

A one-week load measurement for the biggest flour mill showed an average power factor of 0.78 with an average real power consumption of 130 kW. Again at the present penalty rate, it is not economically feasible to install a compensation equipment.

The other big consumer of reactive power in town was the oil factory. A two day load measurement indicated an average power factor of 0.62 with 96 kW active load. Here also individual compensation was not the better alternative for the factory.

Dire Dawa

EELPA's billing register for the biggest consumer, the Dire Dawa Textile Factory, indicates a power factor of 0.75. Before the devaluation of the birr, compensation would have been advantageous for the factory.

CONCLUSION

The preceding analysis shows that, with the present penalty tariff, the EELPA is clearly not exerting enough pressnre on most factories to generate part of their reactive power requirements. The necessary cost for the reactive power generation plants is currently being shifted to the EELPA by way of additional transmission and distribution capabilities.

Therefore, it would seem that the present permissible minimum power factor of 0.85 needs to be raised to somewhere around 0.9. Furthermore, since the cost of capacitors is increasing in terms of birr with each depreciation of the birr, the power factor surcharge needs to be adjusted after every appreciable shift in the exchange rate.

Group Compensation

Installation of capacitors near large distribution transformers, and along distribution feeders and laterals can make sense economically for the EELPA. If the optimum sizes of the compensation plants and their locations are properly chosen, it could be cheaper than reinforcing the distribution network. Although any concrete statement in this regard requires further study, a preliminary analysis shows that a reactive power support under heavy load conditions in the Addis Ababa area is necessary.

Reactive Power in the Transmission System

The EELPA's transmission system is characterized by long transmission lines carrying relatively small power. The total real and reactive power maximum demand for 1996, for example, were estimated at 245 MW and 200 Mvar, respectively. Table 1 shows reactive power demand and generation at peak and minimum loading conditions.

Minimum Load

Under minimum load conditions, all the available reactors are switched on. The voltage profile at most load centers is within the acceptable band. One notable exception is the 132-kV bus at Combolcha, whose voltage is 0.97 p.u. This indicates that the 10 Mvar reactor, which is permanently switched on, is slightly too large.

Peak Load

As one would deduce from the topology of the network and the magnitude of the power which the network is handling, the transmission system has a net generation of 169.4 Mvar even under peak load conditions. In spite of this, since most of the reactors shown in Table 2 are non-switchable, the generators are required to generate a total reactive power of 30.3 Mvar. The permanently switched reactors, which now act as inductive loads, consume a total of 80.5Mvar. The resulting voltage profile at selected points is as follows.

Dire Dawa	0.98 p.u.
Agaro	0.95 p.u.
Buno Bedele	0.94 p.u.
Jimma	0.96 p.u.
Awassa	0.98 p.u.

Table 1: Reactive Power Generation and Consumptio at Minimum and Maximum Loading Conditions

Load Type	Net Losses (Mvar)	Generation		Total Load	
		MW	Mvar	MW	Mvar
Min.	-265.4	84.8	-105.7	82.8	159.7
Peak	-169.4	256.8	30.3	245.4	199.8

Table 2: The Ratings in Mvar of Existing Reactors in the EELPA's System

Substation	Voltage Level		
	230 kV	132 kV	15 kV
Debre Markos	15	_	_
Bahr Dar	15	_	_
Koka	15	_	_
Dire Dawa	15	_	_
Shashemene	_	12	_
Combolcha	_	10	_
Shakiso	_	6	_
Arba Minch	_	_	5
Agaro	_	_	5
Buno Bedele	_	_	5

Installation of Thyristor Controlled Shunt Reactors (TCSR)

The result of the preceding simple analysis indicates that the reactive power management in the transmission system and the voltage stability leave much to be desired.

At least in two points- in Dire Dawa and Bahr Dar- a more flexible form of reactive power injection/ absorption using thyristor controlled shunt reactors seems to be necessary.

Thyristor controlled shunt reactors control the fundamental-frequency current component through the reactor by delaying the closing of the thyristor switch with respect to the natural zero passage of the current.

A TCSR can be built up with a few large steps of thyristor switched capacitors and one or two thyristor controlled reactors . It provides continuously variable reactive output from full lagging to full leading current.

The two locations , i. e. , Bahr Dar and Dire Dawa represent the two extreme points at the moment. When the proposed Tis Abay II project is realized and the expansion of the network to the Northern Region is completed, this bus will attain an added significance in terms of voltage control. Towards the east, the network reaches only Jijiga at present. But it has a potential to expand further in this direction also.

SUMMARY AND CONCLUSION

The EELPA is confronted with an immense challenge of meeting the ever increasing energy demand of the country. On the supply side, the Gilgel Gibe and the Tis Abay II projects seem to have taken off at last. The additional some 210 MW power will certainly go a long way to cover the current acute power shortage and occasional blackouts.

Hand in hand with the anticipated increase in the generating capability, the efficiency, the quality, and the reliability of the supply need immediate attention. In this regard, the voltage stability plays a central role. A lot of work needs to be done in this area.

The suggested increase in the minimum power factor from 0.85 to around 0.9 and its strict enforcement would increase the transmission capacity and reduce the power loss and voltage drop in the distribution system substantially. The significance of this step becomes immediately evident when one notes the fact that the losses in the distribution system outstrip the transmission and generation losses put together.

Although further investigations need to be undertaken, the installation of TCSR at critical points in the network would tremendously enhance EELPA's voltage control capability.

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