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Minimization of Overall Losses of a Distribution System under Contingency Conditions

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Abstract: **In this paper, a methodology has been proposed to minimize the losses of distribution systems (technical and non-technical losses) that is an absolutely necessary objective in the sound management of any electrical utility. The transmission & distribution losses in Indian power system are high. Most of the efforts of power planners concentrate on augmenting supply by building new power plants. But saving is possible by improving operating conditions for the distribution network. Due to inadequate planning and methods adopted for load shifting, some networks are under loaded while others are overloaded. Thus there is some scope for improvement in operating strategies. Network reconfiguration in distribution system is realized by changing the status of the sectionalizing switches and is usually done for loss reduction and avoids overloading. In primary distribution system (11KV), the need for reconfiguration occurs in emergency condition following the fault to isolate faulted section and in normal condition to reduce system losses or to avoid overloading of network. The main objective of the paper is to outline a methodology for management of distribution system for loss reduction by network reconfiguration. The possible techniques used for power loss reduction, which are network reconfiguration and capacitor addition. Case studies were simulated on an interconnected ring main distribution network.**

Keywords: **Load flow, Network Reconfiguration, Distribution System and overall Power Loss**.

1. INTRODUCTION

Saving electrical power has become a major challenge worldwide. However due to the increase in environmental concerns the expansion of power stations that use traditional energy resources, such as coal, nuclear, oil etc., are being considered to be put on hold, forcing existing transmission and/or distribution networks to be used more efficiently [1]. Researchers have shown that a reduction of power loss in the network is much more beneficial than the increase in generation capacity [2]. Traditionally, a well designed network serves its purpose best when it is working under normal operating conditions and power loss are kept at a minimum. Failure of a major component in a ring main network, such as a substation infeed or main distribution line can cause a network to go into an unacceptable state of operation requiring contingency analysis. In this contingency state, the network operators must attempt to control the network defensively, that is, to make the input power to the ring main network as small as possible, by using techniques to decrease losses. This reduction in power drawn by the ring main network will mean less power needs to be supplied by power stations to this network, making more available for other networks, despite the contingency being in effect. A schedule of power distribution has to be developed for a large ring network that reduces the loss. In this way, the available power existing due to the contingency can be more evenly spread, and the number of ring main networks to be load shed could be reduced. The objective of this paper is to investigate a large urban network comprising multiple ring main networks for various contingency cases, while ensuring that network constraints are respected. The developed methodology can be used as guidance by network operators to enable them to deliver power to loads efficiently under contingency conditions and in so doing to help reduce the power intake to the ring main network and the impact on generation capacity. This is especially relevant if the overall power system is running with a small reserve margin as this will make extra power available that could help other networks to continue operating which otherwise may need to be load shed, inconveniencing customers.

2. REACTIVE POWER IN DISTRIBUTION NETWORKS

Most of the electrical loads in distribution networks are inductive in nature. Typical examples are induction motors, transformers and fluorescent lighting. These loads absorb both reactive and active power. The active power is used by the load to perform the work, whereas reactive power is used by the load to sustain the electro-magnetic field. The reactive power is always 90º lagging with respect to active power. The supply of reactive power from the network results in reduced network efficiency due to:

- Increased current for a given load
- Higher volt-drop in the network
- Increase in losses of transformers and cables
- Higher apparent power (S) demand from the supply system

It is therefore necessary to reduce and manage the flow of reactive power to achieve higher efficiency of the electrical network. The easiest method of reducing and managing reactive power is by power factor improvement through shunt capacitors.

3. TRANSIENTS AND CAPACITOR SWITCHING

Capacitor switching offers a greater threat due to its generation of transients in distribution networks, every time it is energized [3]. These transients can be more severe than any other types of transients caused by other equipment such as energizing lines. When an uncharged capacitor is energized, the system voltage is momentarily pulled down. The voltage will then rebound and exceed the system voltage by an amount equal to the difference between the system voltage and the capacitor voltage at the instant of energizing [4]. The overshoot will generate a transient between 1.0 and 2.0 per unit depending on system damping. Switching capacitors in the network is considered as a normal operation on the utility side; however it may have a negative effect on the load side [5]. The frequency transients generated can be magnified on the load side (if the load has low voltage power factor capacitors) and can as well result in nuisance tripping of the power electronic devices. The primary area of concern is typically how capacitor switching transients affect power quality for nearby industrial and commercial loads. The safe range determined in the literature is that the peak transient voltage level should be less than twice the rated voltage.

4. COMPONENTS OF A DISTRIBUTION NETWORK

Underground cables (U/G cables):

U/G cables can be defined as insulated conductors, which are put together and finally provided with a number of layers of insulation to give proper mechanical support and also for heat dissipation purposes. For U/G cables, heat dissipation is an issue. The conductors mostly used for U/G cables are usually Aluminum or Copper. Copper is more expensive, but it has a lower resistance than Aluminum. Copper’s low resistance is generally desirable for power lines to minimize power loss, but also because the increase of heat in a conductor limits the conductor’s ability to carry current [6].

Overhead lines:

An overhead line consists of conductors, insulators, support structures and shield wires. Conductors of overhead distribution lines typically consist of Aluminum, which is lightweight and inexpensive, and are often reinforced with steel for strength. One of the most common conductor types is Aluminum Conductor Steel-Reinforced (ACSR), which consists of layers of Aluminum strands surrounding a central core of steel strands [7]. When working with O/H lines a distinction is usually drawn between the line lengths as short, medium and long lines. These line lengths have different equivalent circuits.

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Power transformer:

The transformer is a valuable apparatus in electrical power systems, for it enables one to utilize different voltage levels across the system for the most economical value [8]. Generation of power by synchronous machines is normally done at a relatively low voltage, which is most desirable economically. Stepping up of this generated voltage to high voltage is done through power transformers. This is done to suit the power transmission requirement, to minimize power losses and increase the transmission capacity of the lines. The transmission voltage level is then stepped down for distribution and utilization purposes [9].

Circuit breakers and switches:

Circuit breakers (CB) and switches are crucial components in a ring main network. The CB serves as a protective device that breaks or interrupts overloads and short-circuit currents [10]. Switches are control devices that can be opened or closed deliberately to make or break a connection. The difference between a CB and a switch is that CBs automatically interrupt abnormally high currents, whereas switches are designed to be operable under normal currents.

5. OPERATIONAL CONSTRAINTS OF A DISTRIBUTION NETWORK

Indian utilities need to comply and adhere to the minimum standards as set out by the IS standard document. It provides the following constraints:

Supply frequency standard:

The IS provides that a three-phase voltage shall be supplied at a nominal standard frequency of 50 Hz. The allowed deviation is ± 3%.

The frequency magnitude must be maintained within the permissible limit:

$$f_{min} \leq |f_1| \leq f_{max}$$

Voltage regulation:

Voltage regulation is an important operational constraint in a distribution network. Voltage regulation is defined as the change in voltage at the receiving-end of the line when the load varies from no-load to a specified full-load at a specified power factor, while the sending-end voltage is held constant [11]. In the ideal case, the voltage level at the load buses would remain at exactly a pre-set value, but in practice this is not possible due to continuing changes in load and system configurations. The IS states that, the voltage at the load side must conform to an acceptable value within ± 10 % of nominal voltage. Thus, if the nominal voltage is 400 V, then the highest voltage should not exceed 440V while the lowest voltage should not be less than 360 V. The voltage magnitude at each bus must be maintained within its permissible limit

$$V_{min} \leq |V_i| \leq V_{max}$$

The percentage voltage regulation can be expressed as:

$$\left[\%VR = \frac{|V_{nominal}| - |V_o|}{|V_{nominal}|} \times 100\% \right] \leq 10\%$$

Voltage drop:

According to Indian standard, the maximum volt-drop constraint during full load running condition should not exceed 5% of the nominal voltage.

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$$\% V_{drop} \leq 5\%$$

Conductor current carrying capacity:

The U/G cables and O/H lines are limited by their current carrying capacity. Thus,

$$\left| I_F \right| \leq I_{F,max}$$

Where,

I_F, and $I_{F,max}$ are the current magnitude and maximum current capacity of U/G cable or O/H line F, respectively.

6. TECHNIQUES USED FOR POWER LOSS REDUCTION

There are energy–efficient techniques available that can reduce or keep distribution power loss down to acceptable levels. These energy-efficient techniques have the additional benefit of improving the reliability and quality of supply of the power network [12]. This will also have a dramatic impact on the total amount of generation capacity needed.

The following energy-efficient techniques are used for power loss reduction:

- Re-Conductoring
- Load Balancing
- New Interconnection
- Addition Of New Feeders In The Network
- Replacement Of Old And Obsolete Equipment
- Energy Management Systems (EMS)
- Reconfiguring The Network
- Capacitor Placement

The following subsections describe some of the above techniques and offer some insights into their effectiveness.

Re-conductring:

Re-conductoring allows the capacity of an existing conductor to be increased by replacing the existing conductors with larger conductors. The size of the U/G cable is an important element as it determines the current density and the resistance of the U/G cable. A lower U/G cable size can cause high power loss and high volt-drop in the U/G cable. Hence, increasing the size of the U/G cable will result in power loss reduction. However, larger-sized cables are expensive and the installation costs of these U/G cables also are likely to forbid re-conductoring as a feasible means of power loss reduction. U/G cable upgrade can only be economically justified for older networks that are operating close to their capacity and / or nearing their life span, where life span is the period of time a cable can operate safely.

Load balancing:

When the loads connected to the three phases of a U/G cable are not balanced, as it is always the case in many distribution networks, it results in increased current flow causing the U/G cables to overload, and resulting in high power loss in the system. In this case, the loads should be shifted to the less loaded U/G cables, to reduce the overloading and hence the imbalance in the system.

Capacitor Addition:

Low PF causes an increase of power loss. The increase in PF is done by adding shunt capacitors in the network, as discussed. To reduce the power loss in the distribution network effectively, shunt capacitors should be connected in any of the following parts of the distribution network:

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- Across individual customers;

- At vantage points on 11 kV feeders;

- At distribution transformers; or

- At 11 kV stations.

Replacement of old and obsolete equipment:

This process involves the replacement of old equipment such as transformers, with more efficient ones. The replacement of old high loss devices with new high efficient devices will improve the efficiency of the whole system. However, higher efficiency transformers are considered to be very costly.

Reconfiguring the network:

One of the most effective power loss reduction techniques in distribution networks is to include in them N/O switches and N/C switches. Network reconfiguration is achieved by changing the open/closed status of the switches, circuit breakers (CBs) and other equipment in the network [13]. The reconfiguration process physically alters the topology of the network to achieve certain objectives. Under normal operating conditions, the network is reconfigured to transfer away loads from heavily loaded feeders and to reduce the system loss [14, 17]. Thus, if a network experiences an outage, the network is reconfigured to restore services, and minimize areas without power, whilst keeping the voltage levels and voltage drops within the desired percentage limits. Power utilities commonly use network reconfiguration to reduce power loss because it does not require new equipment. This is the greatest advantage of this method.

Energy Management Systems (EMS):

An energy management system (EMS) is a system of computer-aided tools used by operators of electric utility grids to monitor, control and optimize the performance of the distribution system. The EMS monitoring and control functions are referred to as the supervisory control and data acquisition (SCADA). This intelligent energy management system is designed to reduce energy consumption, improve the utilization of the system, increase reliability, and predict electrical system performance as well as optimize energy usage to reduce costs.

7. CASE STUDY

The first case study assumes a fault on Cable 1A in RM1.

a) Step 1: set the network to its initial condition operations.

b) Step 2: conduct a load flow study on the network. The steady-state results obtained from the load flow studies conducted are as follows:

RM_1 Load bus voltage level results (V_I)

Table 1 shows the load bus voltage level results for the normal operation configuration.

Table 1: RM1 load bus voltage levels

Load Bus	Voltage magnitude(kV)	% Deviation
LV1	0.372	7.00%
LV 2	0.369	7.75%
LV 3	0.366	8.50%
LV 4	0.372	7.00%
LV 5	0.371	7.25%
LV 6	0.369	7.75%
LV 7	0.372	7.00%

Table 1 shows that the voltage levels at all load buses are within the 10% permissible limit

International Journal of Recent Research in Electrical and Electronics Engineering (IJRREEE)
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RM_1 Cable loading results (IF):

Table 2 shows the loading of U/G cables. The maximum carrying capacities of the cables

Table 2: RM_1 Cable loading of RM_1

Cable	Current magnitude (kA)	% Loading
Cable 1A	0.099	66.0%
Cable 2A	0.108	72.0%
Cable 3A	0.003	3.00%
Cable 4A	0.052	52.0%
Cable 5A	0.079	79.0%
Cable 6A	0.048	48.0%
Cable 7A	0.079	79.0%
Cable 8A	0.000	0.00%

The results presented in Table 2 show that all the cables are within their current carrying capacities.

The results obtained in Tables 1 and 2 show that during normal operations, the network is in a healthy state.

RM_1 Overall power loss

The calculated overall power losses of the original configuration are:

$$P_{loss\,(overall)} = \sum P_{loss\;(Cables)} + \sum P_{loss\;(TRFR)}$$
$$= 109\ \text{kW}$$

Table 3: RM1 Load bus voltage levels due to removal of Cable 1A

Load Bus	Voltage magnitude(kV)	%Deviation
LV1	0.352	12.00%
LV 2	0.351	12.25%
LV 3	0.352	12.00%
LV 4	0.366	8.50%
LV 5	0.364	9.00%
LV 6	0.358	10.50%
LV 7	0.360	10.00%

The results depicted in Table 3, shows that the voltage level of the bus loads, LV1, LV2, LV3 and LV6 are below the permissible 10% limit, with load bus LV2 dropping the highest by 12.25%.

The loading of the U/G cables are depicted in Table 4.

Table 4: RM1 Cable loading due to removal of Cable 1A

Cable	Current magnitude (kA)	% Loading
Cable 1A	0.000	0.000%
Cable 2A	0.200	133.3%
Cable 3A	0.093	93.00%
Cable 4A	0.146	146.0%
Cable 5A	0.020	20.00%
Cable 6A	0.049	49.00%
Cable 7A	0.172	172.0%
Cable 8A	0.000	0.000%

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Table 4 shows that the U/G cables 2A, 4A and 7A are overloaded, with cable 7A having the Highest overload percentage.

RM1 Overall power loss:

The new RM1 overall power loss obtained is:

$$P_{loss\,(overall)} = \sum P_{loss\,(Cables)} + \sum P_{loss\,(TRFR)}$$
$$= 185 \text{ kW}$$

d) Step 4: Observe if there are any busbar voltage violations or overloaded cables; If yes, continue to step 5,

- **Voltage constraints violation**

Figure 1 show that load buses LV1, LV2, LV3 and LV6 have experienced under voltage.

This can be confirmed in Table 3.

- **Cable loading:**

Table 4 shows that cables 2A, 4A, and 7A are overloaded.

The answer at step 4 is therefore yes, hence this takes us to step 5 of the developed efficiency plan.

e) Step 5: configure the open and closed switches and add capacitors simultaneously so that optimum voltage levels, cable loadings, overall power loss and overall efficiency are achieved. Using empirical investigations it is found that for this contingency case the optimum solution will be to:

- Close N/O switch of Cable 8A at station BUSHV6
- Open N/C switches of Cable 3A at station BUSHV8
- Add 1.2 Mvar capacitor at station BUSHV5
- Add 1.5 Mvar capacitor at station BUSHV8
- Close N/O switch of Cable 15 at station BUSHV8
- Open N/C switch of Cable 4A at station BUSHV8

f) Step 6: Simulate the new configuration and extract the new steady-state Vi, IF, $P_{loos(overall)}$.

Table 5: Load bus voltage levels for the optimal configuration

Load Bus	Voltage magnitude(kV)	%Deviation
LV1	0.374	6.38%
LV 2	0.374	6.60%
LV 3	0.375	6.34%
LV 4	0.378	5.55%
LV 5	0.378	5.38%
LV 6	0.375	6.37%
LV 7	0.377	5.83%

Table 5 shows that all the load bus voltage levels are within the permissible limit, with the lowest being LV1 and LV2 with 0.374 kV, and the highest LV4 and LV5 with 0.378 kV.

International Journal of Recent Research in Electrical and Electronics Engineering (IJRREEE)
Vol. 1, Issue 3, pp: (17-25), Month: October - December 2014, Available at: www.paperpublications.org

Table 6: Cable loadings for the optimal configuration

Cable	Current magnitude (kA)	% Loading
Cable 1A	0.000	0.00%
Cable 2A	0.126	83.73%
Cable 3A	0.000	0.00%
Cable 4A	0.000	0.00%
Cable 5A	0.022	21.62%
Cable 6A	0.052	52.31%
Cable 7A	0.027	27.38%
Cable 8A	0.074	73.88%

Table 5.6 shows that all the U/G cables are within their current carrying capacities.

- **Overall power losses:**

The new overall power losses obtained for RM1:

$$P_{loss\,(overall)} = \sum P_{loss\,(Cables)} + \sum P_{loss\,(TRFR)}$$
$$= 80.00 \text{ kW}$$

8. CONCLUSIONS

Power losses in networks are caused by the physical properties of the components in the networks. These losses are inevitable, but can be reduced to an optimal level. The losses that occur in distribution networks are large enough to make efforts to reduce them worthwhile. Hence one should try to find ways of minimizing these power losses under normal or abnormal conditions. Ring main networks are considered to be efficient and believed to have low power losses but this is a general assumption since how they operate under contingency conditions, in terms of efficiency is found not to be well known. Thus, the loss of a major component in ring main network tends to increase the power losses causing power shortage to the network. However, networks can be improved more to work efficiently by using specific techniques to lower the power losses within them and in so doing decrease the input power drawn, easing any strain on power stations that may be running with a low reserve margin. An empirical approach is used by network operators as a guideline to bring about improved network performance and ensure network quality of supply when the system is subjected to contingencies. It was found that by using opening/closing of switches (network reconfiguration) and capacitor addition, power loss reduction techniques in networks ensure that network constraints are maintained under contingency conditions.

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