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Assessment of Energy Efficiency of a Large Interconnected Distribution System with Voltage Security Consideration

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***Abstract*: In a situation, where there is a shortage of power generation or the power stations are operating with a very low reserve margin, as is typically the current position in INDIA, there is a need to operate distribution network at the highest possible efficiency by utilizing network power loss reduction techniques. Such techniques are especially important when contingencies occur as they tend to increase loss, reduce efficiencies and cause power supplies to such networks to increase. This increase can cause the network or multiples of such networks to be load shed, as the power stations do not have the reserve margins to meet this increased demand. An efficiency schedule has been developed for a large ring network that reduces the loss so that its input power can be decreased. 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. From the obtained results, the developed efficiency schedule for a large ring main network under contingency conditions was shown to be effective. The efficiency schedule is thus recommended for application in this important field as it will help to prevent load shedding, especially in the situation where power stations are operating with low reserve margins.**

***Keywords*: Load flow, energy efficiency, ring main system, overall losses, and load shedding.**

I. INTRODUCTION

Many approaches regarding power loss reduction in distribution systems have been proposed over the years. Some researchers used optimization methods, while others used expert systems, or heuristic methods. Many of these methods were developed for radial networks, which are simpler for investigations, however most large urban distribution networks are not operated as radial networks. Also localized areas of a national grid, called "distribution" comprises of many interconnected large urban ring main networks [1]. When operated together they pose great challenges in regard to power loss reduction. Some of the methods applied to reduce loss in radial systems cannot be applied to the power loss analysis of ring main networks. Further, although ring main networks are believed to have less power loss compared to radial networks, loss of an important component in a ring main network can cause an increase in power loss. This may cause a power shortage in the network. There is also a limited explanation of efficient operation under contingency conditions. There are also no studies found in literature on the efficient operation of a large urban network comprising multiple ring main networks. This is a shortcoming in literature. Thus, there is a need to develop a plan for such a network that shows how to deliver electrical power to loads efficiently under contingency conditions. The objective of this paper is to investigate a large urban network comprising multiple ring main networks and develop an efficiency plan for various contingency cases, while ensuring that network constraints are respected. The developed efficiency schedule 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 [2]. 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. Under contingency operations, the losses in a network generally increase above that occurring under normal operations. The importance of this project is to ensure that the power lost in ring main networks due to contingency conditions should no longer be ignored. This will help network operators and energy conservationists to determine the power loss in the network and assist them with measures that can be taken to reduce these losses. An efficiency schedule, in a form of a flow chart, which is unique, is developed for conducting the investigations [3-4].

II. OVERVIEW OF A DISTRIBUTION SYSTEM AND ENERGY EFFICIENCY

Electrical energy is transferred through an extensive grid from the sources of power to the consumer points [4]. A power grid generally consists of three identifiable parts, namely: generation, transmission and distribution. Electric power is generated at generating stations. The generation system produces electrical power in medium or low voltage, usually between 6.6 kV to 11 kV. This voltage is stepped up to high voltage for transmission at the step-up substation. The electrical power is transmitted from the step-up substation across long distances by the transmission system. The transmission system is composed mainly of transmission lines, transformers, and protective devices. The sub transmission system transmits power in smaller quantities from the transmission substations to the distribution substations. Large industrial customers are commonly supplied directly from the sub transmission system. The distribution system represents the final stage in the transfer of power to the individual customers. The primary distribution system is typically between 11kV and 33 kV. The primary distribution system transports the electrical power by distribution feeders which can be overhead distribution (O/H) lines or underground cables (U/G cable) to the distribution transformers that step the primary distribution voltage down to utilization voltage, to supply a secondary distribution system to which the loads such as residential, commercial, etc… are connected [5]. The overall system thus consists of multiple generating sources and several layers on transmission networks. This provides a higher degree of structural redundancy that enables the system to withstand unusual contingencies without service disruption to the customers [6].

It is estimated that the average power transmission loss from power utilities amounts to around 5% -6% of total power demand, whereas 60%-70% of these losses are estimated to be lost in distribution networks [7]. Electrical energy efficiency is one of the measures of saving energy used to provide goods and services while maintaining the desired benefits [8]. Electrical energy efficiency includes efforts to reduce energy usage in a particular area with the goal of reducing energy usage and peak-load demand in the network. In contrast to supply options, energy efficiency puts downward pressure on reducing demand instead of increasing supply [9]. This means that energy efficiency provides additional economic value by preserving the resource base and reducing the pressure on the environment [10].

III. COMPONENTS OF A DISTRIBUTION NETWORK

3.1 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 [11].

3.2 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 [12]. 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.

3.3 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 [13]. 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 [12].

3.4 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 [14]. 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.

IV. CONTINGENCY ANALYSIS

Contingency analysis is one of the crucial power system studies. It refers to the security of the system operation under the loss of one or more of the major system components due to a failure [15]. In the case of a loss of one component, this corresponds to the N − 1 criterion, i.e. the system should be able to support the load when one of the N basic transmission system components e.g transmission line, generator etc. is out of operation [6]. The application of the criterion can also be extended to the case of loss of a combination of these basic components. When applied to the loss of two components, it leads to the N – 2 criterion [6]. Contingency analysis helps to look at the system's vulnerable points and helps in obtaining through simulations, standard solutions which will enable the operator to react in real time situation to resolve the problem in a short time. Ring main networks are not immune to the contingency scenarios. It is therefore very important that networks be studied under these conditions to note any overloads or voltage violations in excess of constraints and to implement preventative and corrective actions required to ensure continuity of supply.

V. RESERVE MARGIN

In extreme cases, with all generators fully loaded, if one generator fails because of a low reserve margin (2% to 3%), some service to customers will be inevitably interrupted. To avoid this type of situation, utilities have traditionally retained a high reserve margin (±15%) of generation [16].

VI. BENEFITS OF IMPROVING EFFICIENCY

Electricity generation accounts for a huge portion of unwanted carbon emissions into the atmosphere. Greater energy efficiency in the distribution system means lower emissions from generation to deliver the same amount of energy to the consumer. Reducing energy losses in a distribution network will also reduce the overall system demand and provide additional network capacity for utilization and growth. Since energy losses costs are passed onto all loads, improvements in this area will benefit all loads. Efficiency improvement also reduces the risks of load shedding during contingency conditions.

VII. EFFICIENCY PLAN METHODOLOGY

Figure 1 shows an efficiency plan work-flow diagram. The work-flow diagram depicts an empirical approach for finding the optimal configuration that will minimize the power losses in a ring main network that is under a contingency condition, while satisfying the given constraints. The flow diagram was evaluated using the ring main network in Figure 1. The load flow procedures find a series of configurations with different status of switches and addition of capacitors such that the power losses are successively reduced. The network was analyzed using dedicated tool of MATLAB software to obtain steady-state and time domain results, respectively. The load flow procedures of the proposed method are mainly composed of power loss and efficiency calculations, bus bar voltages and cable/feeder loading determination and empirical approach application. In Figure 4.3, k is the number of U/G cables / O/H lines or substation infeed to be considered, its value can be any positive number; V_i is the bus bar voltage level measured in Kilo-Volts (kV); V_{min} and V_{max} are the minimum and maximum permissible voltage levels of a bus bar respectively; I_F and $I_{F,max}$ are the current magnitude and maximum current capacity of a U/G cable F or O/H line F, respectively; $P_{loss(overall)}$ is the overall power losses of the network; $\square_{overall}$ is the overall efficiency of the network [17-18].

7.1 Under Ground cable outage

Step 1: Create a steady-state computer model of the network in its normal operating state.

Step 2: Simulate a load flow and obtain the normal operation (original configuration) voltage levels (V_i) of the load busbars (LV), the U/G cable /O/H Line current loadings (I_F) and calculate the overall efficiency ($\eta_{overall}$). This will help the operator to know the normal operating conditions of the network.

The overall efficiency ($\eta_{overall}$) is obtained by:

$$\eta_{overall} = \frac{\Sigma P_{out(X)}}{\Sigma P_{in(X)}} \times 100\%$$

where, $\sum P_{in(x)}$ and $\sum P_{out(x)}$ are the total input and output power of network X respectively.

Step 3: Select a cable, F, to be out of service, perform a load flow for this contingency condition and extract the network's new V_i, I_F, $\eta_{overall}$. These results will help in measuring the severity of the contingency condition under study.

Step 4: Observe if there are any busbar voltage violations or overloaded cables; If yes, continue to step 5, if no, Jump to step 7. The following constraints are taken into consideration:

- Voltage constraints (limits)

Supply voltage to loads within ±10% of the busbar nominal voltage during both normal and abnormal operating conditions in the network.

- Current loading constraints

It is important to ensure that the primary cables are not overloaded more than their rated capacity.

Step 5: Determine the best configuration of open and closed switches (network reconfiguration) and capacitor addition simultaneously. The simultaneous solution of the optimal reconfiguration and capacitor placement problem determines which network switches should be open and which closed as well as capacitor sizes and locations in order to reduce losses, to improve voltage profile and, in a more limited way, satisfying equipment and operational constraints.

Step 6: Extract the new V_i, I_F, and $\eta_{overall}$. These results will show you the effectiveness of the efficiency plan.

Step 7: Check if $\eta_{overall}$ has improved. The configuration that results in maximum power loss reduction should be considered as the optimal configuration.

Step 8: Continue to the next cable *(F-1)*.

Step 9: Check if all cables are considered, if not go to step 3.

Table 1: RM1 load bus voltage levels for the optimal configuration

Load Bus	Voltage magnitude(kV)	%Deviation
LV1	0.367	8.21%
LV2	0.365	8.81%
LV3	0.364	9.12%
LV4	0.366	8.46%
LV5	0.367	8.35%
LV6	0.366	8.49%
LV7	0.368	7.96%

The results presented in Table 1 show that all the voltage levels for the load buses are within the 10 % limit.

Table 2: RM1 cable loadings for the optimal configuration

Cable	Current magnitude (kA)	% Loading
Cable 1A	0.080	53.11%
Cable 2A	0.094	62.78%
Cable 3A	0.029	28.76%
Cable 4A	0.042	42.37%
Cable 5A	0.060	60.10%
Cable 6A	0.035	34.94%
Cable 7A	0.067	67.23%
Cable 8A	0.000	0.00%

Table 2 shows that all the U/G cables are within their maximum carrying capacity.

- **Overall efficiency for RM1**

The total input power supplied to RM1 from VS RM2 via cable is $P_{in(cable)} = 2.952$ MW, and □ $P_{out(cable)}$ is 2.866 MW. Thus, the total input power to RM1 is:

$$\sum P_{in\,(RM1)} = P_{in\,(cable13)} = 2.952\ \mathrm{MW}$$

Hence the overall efficiency of RM1 is:

$$\eta_{overall} = \frac{\sum P_{out\,(RM1)}}{\sum P_{in\,(RM1)}} \times 100\% = \frac{2.866}{2.952} \times 100\% = 97.10\%$$

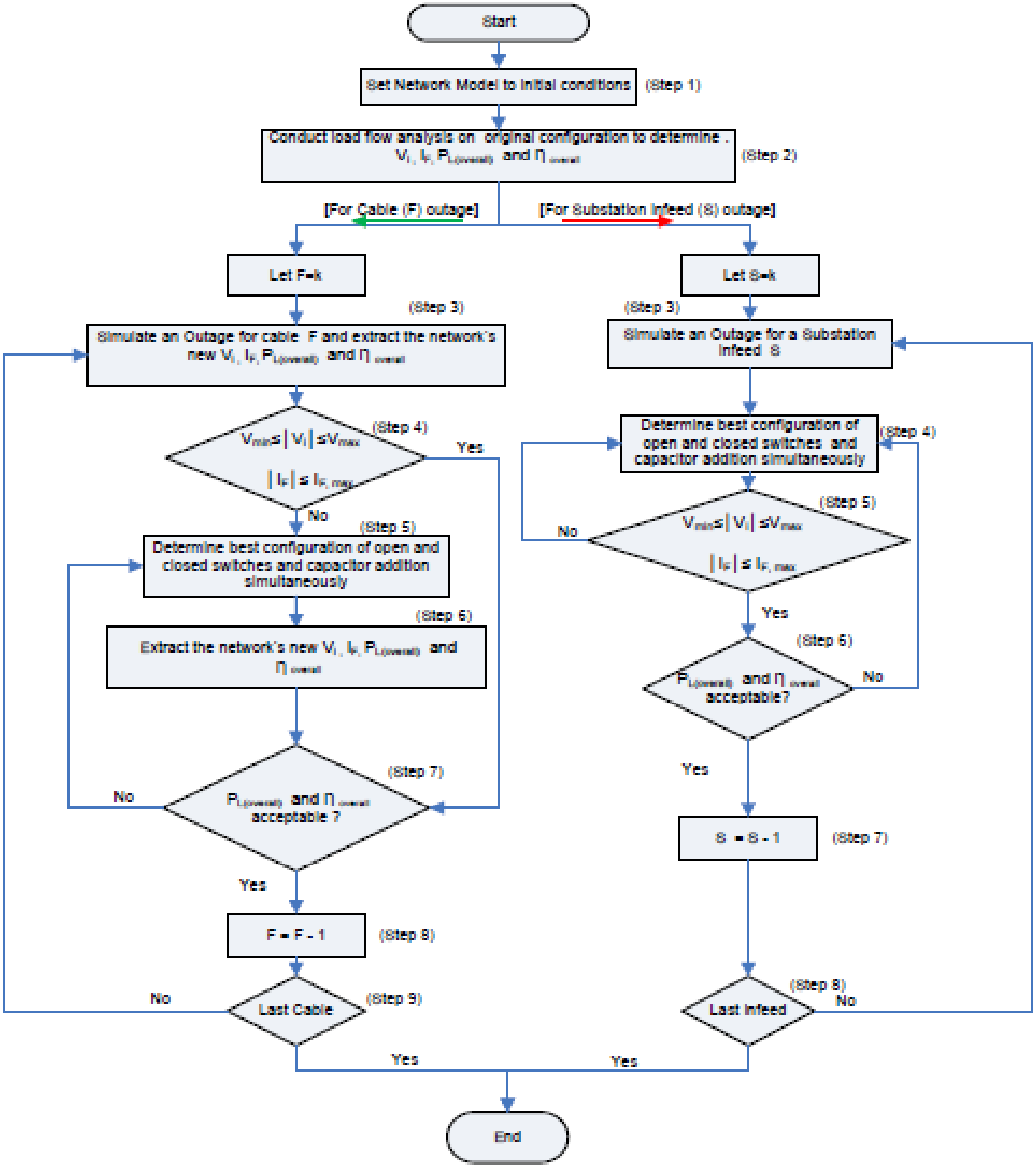

Figure 1: Efficiency plan: work flow diagram

RM1 Overall Efficiency

Figure 2 shows that RM1 is operating at a high efficiency during the optimal configuration compared to the normal operation efficiency. The efficiency has increased by 0.71%. After the RM1 load was transferred to RM2, the RM2 overall efficiency increased from 96.42% to 97.10%.

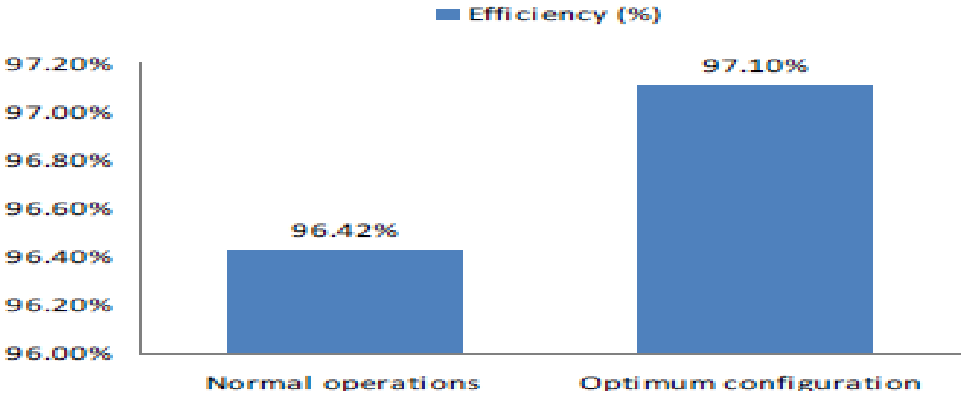

Figure 2: RM1 Overall efficiency for case study 1

VIII. CONCLUSIONS

The developed efficiency plan, in the form of a flow chart, which is a novel contribution to the studying of power loss reduction under contingency conditions has been shown to be effective and is recommended for use and/or application by industry. The plan can be easily adapted so that it can be applied to any large urban ring main network and even to multiple ring networks. Case study considered a contingency case (N-1) of Cable and a loss of substation infeed v/s RM1 (N-1) was conducted to apply and evaluate the effectiveness of the efficiency plan.

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