Chapter 1

Introduction

1.1 Distribution Systems and its Basic Structure

Distribution system brings electricity to the end consumers. Conventionally, it did not have any generating resources embedded in it. Thus, in conventional distribution system power flows are expected to be unidirectional. The distribution systems are commonly modelled as radials of certain length distributing power in one direction i.e. from source end to the load ends. The issues such as safety, protection and coordination, network planning and operation, power quality and design of system components are dictated by this radial architecture of the distribution systems.

Though, radial distribution architecture is simplest and cheapest, double circuit or loop architecture gives redundancy in the system. Modern distribution systems have embedded/active generations, and bidirectional flows. The possibility of bidirectional flows has given rise to several challenges for the protection of distribution systems. This complexity of modern distribution systems calls for intelligent distribution management systems (DMS) having large amount of Information and Communication Technology (ICT) components. The deployment of intelligent DMS has also given way to operation of the distribution systems in meshed configuration.

1.2 Problems of Distribution Systems

A distribution system serves unbalanced three-phase, two-phase and single-phase loads. A physical transmission happens over untransposed conductors. This fact along with variation in the types of loads naturally makes the distribution systems characteristically unbalanced. Other problems associated with distribution systems are under-voltage and over-voltage. The increase in voltage above 110% of the nominal voltage for more than 1 minute is termed as over-voltage. This phenomenon usually occurs due to improper compensation and outage of heavily/lightly loaded lines. The under voltage limits are below 90% of the nominal voltage for more than 1 minute. The under-voltage phenomenon is quite common in distribution systems due to its radial configuration especially at the far ends of distribution systems. There are several research papers in the literature addressing the mitigation of under-voltage/over- voltage problems through reactive power compensation. Capacitive compensation can also be seen from the perspective of power factor correction in the system, as the present distribution systems caters mostly the lagging loads. The low power factor forces high currents in the systems calling for larger conductor sizes and larger equipment sizes and increase in system losses. Higher currents at low power factors also adversely affect voltage regulation.

The problem of under-voltage/over-voltage and losses may also be addressed through reconfiguration of distribution network. Reconfiguration is essentially done using tie-lines provided in the system for redundancy against faults to ensure service of loads by rerouting the power to the systems loads in the event of line outages. The rerouting may result in a new configuration giving lower losses hence option of reconfiguration can also be exercised for loss minimization.

Other problems associated with distribution systems are voltage sag/swell which are short-time (greater than 10 ms and less than 60 s) phenomenon. Reduction in voltage level in the range of 10 - 90% of the nominal RMS voltage is considered as voltage sag and rise in voltage from 110 to 180 % is termed as voltage swell. Voltage swells are usually caused by system switching operations, sudden change in ground reference, single line-to-ground fault leading to voltage rise in unfaulted phases for the duration of fault. Similarly sags are caused by faults on distribution networks, faults on consumer equipment, and switching in of heavy loads.

Other short-time phenomena in distribution systems are voltage interruption, voltage transients, voltage fluctuations and flicker, dc offset, and harmonic distortions.

Increased presence of small generating resources embedded within distribution systems has made many of the assumption incorrect with regards to the radial nature of the distribution systems. Distribution networks are no longer passive networks; thus basic premise that a radial feeder would become dead upon opening of breaker, cannot be taken for granted as embedded generation would still be feeding the line.

1.3 Problem of Feeder Unbalance: Phenomenon and Causes

The fact that variation in the types of loads naturally makes the distribution systems characteristically unbalanced, affects the distribution system in various ways. The working of several relays in the distribution systems are sensitive to the sequence currents in the systems and have a tendency to maloperate.

Unbalance of phases in the distribution systems can manifest in the form of current unbalance and/or voltage unbalance. The voltage unbalance in the system can happen due to unbalance of parameters of components such as generators, transformers, and feeders (due to untransposed lines). The voltage unbalance also occurs due to unbalanced phase currents leading due to asymmetrical voltage drops in individual phases. Thus current unbalance also leads to voltage unbalance. Current unbalance mainly occurs due to single phase loads or two-phase loads and also occurs in balanced load condition in the presence of voltage unbalance. Thus these two phenomena are tied together.

The main substation transformers are one of the costliest devices in the distribution system. The MVA capacity is divided equally on three phases hence, the per-phase capacity is one-third of the MVA capacity of the transformer. As the time progresses the system load grows, however usually the load growth may not be equal on three phases. When the system loads are severely unbalanced, then if any of the phases gets loaded up to its capacity, the further loading of the main transformer gets restricted even when there may be sufficient capacity available on other two phases. This may lead to load shedding on the loaded phase. Thus, in any system the load shedding limit would always be less than the total MVA capacity of the transformer.

The phase unbalance in a system can create large voltage differences among the phases at a bus. The unbalanced phase voltages lead to unbalanced currents in three-phase loads at the customer site. This further restricts the transformer capacity at the customer site. Also, the unbalanced three phase load means higher negative- and zero-sequence current leading to losses for consumers which is not due to consumer.

Also, in several cases the severe unbalance may not allow the consumer to use the machinery effectively because the voltage unbalance results in reverse magnetic fields which in turn results in rise of the temperature of machine winding and fall in the output torque. The unbalance in the system creates negative- and zero-sequence currents to flow in the system. The neutral conductor in the system is designed to carry small current compared to other phases assuming that the phases are balanced. The increased unbalance may ask for increased rating of neutral conductors. The neutral has a higher resistance compared to other phases and therefore, increase in neutral current increases the neutral losses also.

1.4 Methods of Achieving Feeder Balancing

The mitigation of phase unbalance can be achieved through following means.

1. Use of power electronic components such as Dynamic Voltage Restorer (DVR),

2. Unified Power Flow Controllers (UPFC),

3. Single phase voltage regulators,
4. Shunt reactance balancing compensator,
5. Series reactance balancing compensator, and
6. Suitable combinations of above.

The methods 1 through 6 involve power electronic, transformers, and switching arrangements to achieve the goal of unbalance mitigation. However, due to load growth and changes, the above methods may demand periodic upgrade and tuning of equipment and their setting respectively. This may also demand other inherent drawbacks such as injection of harmonics.

The other ways of ensuring balance in distribution systems are implementation of regulations and standards for all the system components on utility as well as customer side. However, this has practical limitations especially on the smaller customers who are served by the single-phase supply. Also, it may become a practice restrictive to business for the utility even for larger customers. Thus, more or less, it is a requirement of utility to achieve balance in the system.

There are two possible approaches to achieve balance in the distribution systems. One is through switching of loads from one phase to the other phase and second approach is through switching of sources in the similar fashion. Load switching from one phase to another through a simple switch arrangement shall be practical for the utilities without imposing restrictions on the customers especially fed by single phase and two-phase where customer equipment and appliances are not sensitive to the phase sequence. However, this method has a limitation that this switching may cause a short-time supply interruption, thus this switching can be carried out only for a limited number of time when unbalance goes beyond a tolerance limit set by the utility/standards. In any case, if the intolerable unbalance is not addressed timely, the system will lead to shut down. In the present work applicability of load switching for unbalance mitigation has been studied.

Switching of sources to achieve balance in the distribution system has become possible to presence of embedded single-phase sources in the system. Presence of embedded small captive as well renewable power plans in the system can be leveraged to obtain balance in the systems. This approach is also a subject of study in the present work.

It is worth noting that planning and operational decisions of distribution systems are made on single-phase basis assuming balanced system even in the present scenario. The unbalance in voltage and current were in consideration in perspective of motors and generators by ANSI/NEMA, and IEEE [3]. The analysis of accuracy of true definitions and formulas were further carried out in [4, 5]. A reference to using unbalance as a quality measure in distribution systems is found in one of the documents of the BC Hydro namely ES55 Design Standards Q4-07−Voltage Unbalance, medium voltage customer Emission limit, British Columbia Hydro & Power Authority, issued: March, 2016 [6]. The document describes the calculation of voltage unbalance and limiting criteria for customers of type "standard" and "rural" limits. The standard calls for the compliance on the customer side based on customer emission assessment.

A methodology to provide statistical estimates of unbalance is presented in [7]. The authors used the distribution system state estimation method to assess the level, location, and impact of voltage unbalance on a distribution system. Z. Liu and J. V. Milanovic [8] used Newton-Raphson Load Flow along with Monte Carlo simulation to determine the range of voltage unbalance on a given bus. The method utilized historical data of load for giving a probabilistic estimate of voltage unbalance. The assessment of voltage unbalance from source point of view was attempted by Dhaphne Shwanz et al. [9]. The authors made stochastic assessment of voltage unbalance for single-phase photovoltaic inverters in a distribution network. The work evaluates different networks viz. Swedish and German networks for possible impact of single-phase photovoltaic inverter on voltage unbalance.

The hardware employed for phase-balancing have their associated losses and cost of implementation and inject harmonics. Cheng-Che Chen and Yuan-Yih Hsu [10] developed design of a shunt active filter for balancing three-phase four-wire system even under non-sinusoidal conditions. The approach does not require the transformation of phase voltages and currents into alpha, beta, and 0 quantities.

The power factor of the positive-sequence fundamental component is kept close to unity. Douglass and Trintis [11] proposed three-phase active front end rectifiers for reducing unbalance in low voltage distribution system. A prototype design and test results on this prototype show that a significant reduction in voltage unbalance can be achieved throughout an LV feeder shared by several residential units.

1.5 Feeder Load Balancing using Re-phasing of Loads

It is also possible to interchange the load being fed from one phase and neutral to another phase and neutral through a switch. The load interchange mechanism has less hardware requirements and makes use of natural unbalance of the network. There are different criterion on basis of which the load may be interchanged from one phase to another. The criteria could be (i) to balance the system loads so that all phases draw equal current from the main substation utilizing the full capacity of the main transformer; (ii) to reduce the losses of the system by reducing the neutral current; (iii) to have minimum current in the neutral conductor; (iv) to have balanced three-phase voltages at all the system 3-phase buses; (v) to reduce the flow of negative- and zero-sequence currents to avoid maloperation of relays.

It is one of the problems for which search based methods such as Genetic Algorithms (GA) or Particle Swarm Optimization (PSO) are best suited. There are other methods based on heuristics; such as fuzzy logic based techniques for getting a better phase balancing scheme [12]. GA-based approach has been proposed to solve phase-balancing problem along with other objectives in a weighted form [13]. The authors have also indicated that when compared with other heuristic methods of phase balancing the GA performed better. The advantage of load-time characteristics of different load types in a distribution system can be taken for re-arranging the transformer phases for obtaining load balancing.

With adoption of new technologies focused towards smart-grid operations there is a need for serious attempts towards implementing some of the useful functions such as phase-balancing in distribution systems. The implementation of automation and measurement technologies have given some interesting insights into characteristics of distribution system operation such as increase in system power consumption despite implementing loss reducing strategies such as capacitor placement [14], under voltage load shedding [15], and feeder phase-balancing in certain conditions [16]. These phenomena were observed through practically acquired measurements, whereas, most of the studies in literature showed otherwise [?]. It is evident that automation technologies adopted would be useful only if proper model are used in operational studies. One of the simulation assumptions which need a serious review is load (model) representation in system operation studies.

An analysis of implications of not using appropriate load models in operational studies must also be assessed. An important point made by authors in [16] regarding the impacts of unbalance compensation on feeder losses was that it may lead to slight increase in feeder losses. The two major effects of unbalance compensation were found to be as follows,

(i) unbalance compensation usually leads to loss reduction. The reduction in certain case could be to the tune of 15%.

(ii) elimination of unbalance components at the low voltage bus of substation causes a slight increase in feeders losses.

The first case is obvious; due to reduction in line flows of zero-sequence and negative-sequence currents in the circuit, the losses attributed to them would reduce. However, the second case is not very clear and is one of the subjects of investigation in this paper. It is shown that (ii) can be explained if the voltage-dependency of loads were considered.

In the present work a particle swarm based load balancing is implemented. First of all, the extent up to which a feeder phase balancing can be achieved through re-phasing of loads is demonstrated.

This thesis investigates the voltage-dependency aspect of load and attempts to come up with a possible answer to some of the phenomena which have been reported in literature from field studies which do not match with the theoretical estimates [16]. The current-injection based [17] load flow is modified for inclusion of voltage-dependency of loads. The thesis also discusses the detailed outcomes of phase-balancing in terms of MVA intakes, losses, bus voltages, main substation transformer loading margins, phase currents and sequence currents.

1.6 Feeder Load Balancing using Re-phasing of Single Phase DGs

As discussed earlier, the modern distribution networks are characterized by embedded generations. Several of these embedded generations are single-phase generations and are also dispatchable. The single-phase generations can be scheduled for balancing the systems phases. When single-phase loads are switched from one phase to another, following problems occur.

(i) It causes momentary interruption in the load service to the customer.

(ii) It results in change of phase sequence of the load and therefore is not suitable for sequence sensitive loads and thus limits switching of sequence sensitive loads.

An attempt for voltage unbalance compensation has been made using distributed resources and responsive loads in islanded microgrid [11], however switching of single-phase DGs for load balancing can also alleviate the above problems. Penetration of DGs in the distribution systems offers possible solutions for phase balancing which present work seeks to explore. The work in this thesis examines use of single-phase DGs and reactive power support to reduce the phase unbalance at the root node. This has been performed in two steps. In the first step, optimal sites of a fixed number of single-phase DGs are finalized. In the second step, the optimal phase allocation along with sizing of the single-phase DGs has been performed.

1.7 Motivation and Objective of the thesis

Distribution systems are getting equipped with Information and Communication Technologies (ICT). Various problems of distribution systems which were considered acceptable in conventional distribution systems have now become solvable.

The problem of phase unbalance was not much severe as the amount of load served were less, also the protection philosophy was quite systems and unbalance was not seen as a major hindrance to the system operation. As the distribution systems grew in size, capacity, and in terms of information and communication infrastructure, the problem of unbalance became significant as well as solvable.

This work considers the availability of communication, control and computational infrastructure for solving the problem of unbalance in distribution systems.

The objective of the thesis can be enumerated as follows.

1. Development and testing of reliable and robust three-phase power flow algorithm for unbalanced systems. The developed power flow is envisaged to have capability to handle large number of PV buses which would be feature of upcoming distribution systems.

2. Development of phase balancing algorithm for conventional distribution systems considering switchability of loads from one phase to the other. Further, the test of efficacy of the developed algorithm is to be carried out in terms of amount of unbalance mitigation.

3. Development of phase balancing algorithm for distribution systems with large number of embedded single-phase generations. Further, the test of efficacy of the developed algorithm is to be carried out in terms of amount of unbalance mitigation.

1.8 Outline of the thesis

In chapter 2, an improved CINR load flow method has been presented. The developed load flow uses the new equations to model the PV bus in current injection power flow formulation, which is based on real and imaginary parts of simple multiplication of voltages and currents of PV buses. The new CINR, Mod-CINR, load flow technique decreases the required number of equations and also recovers the convergence property of revised current injection load flow methods same as conventional NR (CNR) method in the case of PV nodes particularly. At heavy load and large R/X ratio conditions also the convergence characteristics improved. The results have also demonstrated that the computation time of Mod-CINR is less than the fast decoupled NR (FDBX) methods in the absence of PV buses in systems. All the experiments suggest that the performance of the improved method in comparison with other techniques is better regarding convergence, efficiency, sensitivity, and reliability.

In chapter 3, the optimization techniques used in the chapter 4 and 5 have been described in the context of the problem addressed in the thesis.

In the chapter 4, it has been demonstrated that re-phasing is sensitive to voltage-dependency of loads. It was found that the voltage improvement due to re-phasing increases the load demand. The increase in load demand at individual buses may be insignificant, but for a system as a whole it is significant enough to reverse the advantage of loss reduction conventionally expected due to re-phasing. It was found that the system after re-phasing may suggest more MVA margins at the main substation if appropriate load model is not considered.

Two optimization algorithms, i.e., PSO and Butterfly Optimizer (BO), have been successfully applied for feeder re-phasing of radial distribution network. The PSO based method was compared with GA based method on a system reported in the literature to establish the effectiveness of the approach. To further validate the effectiveness of the proposed approach a 24-hour load pattern was taken. It was found that the system could be balanced substantially in terms of phase currents, phase voltages and losses per phase. The energy losses for the system reduced from 9.33% to 8.45% which was reduction of 9.43% on relative terms. One more method has been attempted.

In chapter 5, DG planning for the purpose of phase balancing has been proposed. The planning is approached in two stages. In stage 1, the optimal DG locations (phase and bus) and sizes are obtained for peak load scenario. The location are then considered to be fixed and the sizes obtained are taken as maximum available DG real and reactive capacity at the given buses. In the stage 2, the DGs are optimally scheduled hourly (in term of phase and size) for 24-hour loading scenario to obtain the phase balancing. It has been established that an effective phase balancing can be achieved with help of single phase DGs scheduled in this fashion. The reduction in losses and the improved voltage pro le are added advantages. Detailed analysis to ascertain the effect of voltage dependency of loads on optimal scheduling of DGs establishes that for pragmatic optimal solutions, the voltages dependency of loads must be considered albeit in approximate sense rather than doing the same using constant power load model.

In this chapter also BO and PSO have been successfully applied for single-phase DG re-phasing of radial distribution network.