CHAPTER I

INTRODUCTION

1.1. PREAMBLE

Nowadays, electric supply has become indispensable power to drive all the economic activities of any country. Therefore, the challenges of power industries are increasing day by day. As a consequence of these challenges, Wide Area Measurement System (WAMS) has been incorporated and established in the system in order to tackle such vital challenges. WAMS based on synchrophasor technology provides the real time monitoring, operation and control with the abilities of advanced communication infrastructures. The capabilities of WAMS that is data for entire system at a same time and the same place i.e. control center, makes the WAMS more reliable as compared to traditional power systems. Previously these measurements have originated using Supervisory Control and Data Acquisition (SCADA) system. Whereas, synchronized monitoring of the power network is hard to attain using SCADA system. The WAMS consists of Phasor Measurement Units (PMUs), which are highly accurate and advanced time synchronized technology.

The PMUs provide the voltage and current phasors and frequency information through Global Positioning System (GPS) receivers that allow the synchronization of several readings taken at distance points. Phasor Data Concentrator (PDC) collects the data from all the PMUs which are directly connected to the PDC through communication links. As technology advanced, the time frame of synchronized information steadily reduced from minutes to microseconds. In some applications, the use of PMU technology is most suited, while for others such as congestion management [1], the PMU technology could provide lesser advantages and improvements. The installation cost of WAMS is too high due to higher cost of PMUs and communication facility between the buses of the system and PDC, therefore it is uneconomical to install the PMUs at all the buses and make the system full observable. Thus an optimal placement of PMUs is required to minimize the installation cost of WAMS. During the contingency in the system, observability of the power system may be lost. Therefore, most of the researchers in this area incorporating the contingency cases (e.g. single PMU outage, single line outage or both together) in formulation with the optimal synchrophasor measurements which makes the system more reliable and secure during the contingency cases.

Current society is very vulnerable in case of the power system blackouts, as the consequences of blackouts being both social and financial. Even a small disturbances may be harmful for the process industries, due to restarting of procedure that might take several hours, also for air traffic control and areas that depends on the computers. Therefore, these consequences of disturbances in office work will be loss of production and information. Many services will be at standstill, because the production or use of service requires electricity. Long disturbance complicates the use of communication systems, water distribution, storage of food stuffs, traffic and transportation etc.

In the recent past, number of blackouts have been encountered in the power system. These blackouts have happened because either of voltage or angle instability or both together was not detected within the time and progressive voltage or angle instability further degraded the power system condition. Voltage instability which has caused most of those wide area blackouts has become one of the global concerns for system operators. Until now several techniques have been developed to moderate this problem. After the development of synchrophasor measurements, the scanning rate of dynamic changes in the system increased and the calculation time significantly decreased due to real-time phase angle measurement in spite of using traditional phasor estimation techniques.

This work presents a novel meta-heuristic technique known as Binary Gravitational Search Algorithm (BGSA) in order to optimize the number of synchrophasor measurements in power system which also provides the maximum observability of the system. Therefore, in the formulation of problem objective, two objectives are incorporated. First objective is to optimize the number of PMUs in the system and second objective is to maximize the observability of the system. Thus the PMU placement problem is expressed as a multi-objective problem. The installation cost of WAMS is not only dependent upon the cost of synchrophasor measurements. It also depends upon the cost of communication infrastructures of WAMS. Therefore, further the cost of communication infrastructures is incorporated in the objective function of OPP problem. Some of the literature proposed various OPP techniques while considering the particular cases such as state estimation [2]-[3], islanding [3]-[4], voltage stability [5] and fault location [6] etc. Whereas, PMU placement once performed is single time exercise. In such scenario, for new application, it would be uneconomical to further add PMUs into the system. Therefore, a particular case which covers maximum applications and contingencies in the system should be incorporated into the OPP formulation. Considering above problem, this work proposes the OPP technique, which may perform effectively in various applications of WAMS. This work presents a voltage stability assessment index using synchrophasor technology in power system. Detailed descriptions about the proposed OPP techniques and voltage stability assessment are discussed in the later chapters.

1.2. WIDE AREA MEASUREMENT SYSTEM

1.2.1. History and definition of WAMS

In the last few years, many developments have been done in WAMS to monitor the system dynamic behavior. WAMS is the intelligent technique which provide continuous identification of the system states. WAMS provide the dynamic view of power system in real time. WAMS was firstly introduced by Bonneville Power Administration (BPA) in 1980 [7]. Because of the Western System Coordinating Council (WSCC) challenged a critical absence of dynamic information during the 1980s. Therefore, the Western Interconnection of North America power system was the first one who implemented the WAMS. In 1995, a project has been started by the US Department of Energy (DOE) and the Electric Power Research Institute (EPRI). The main aim of this project was to provide the real time dynamic data of Western System. Moreover, WAMS provides the system reliability during deregulation and restructuring process [8]. Since 1994, PMUs have been incorporated in WAMS and they have provided synchrophasor measurements [9]. WAMS may contribute in previous functions or some new functions which are not achieved previously by the conventional measurements.

A specific and comprehensive definition of WAMS has been introduced by *Taylor* [7]:

“The WAMS effort is a strategic effort to meet critical information needs of the changing power system”.

Another definition by *Taylor* [7] in terms of infrastructure to perform its tasks is as follow:

“The WAMS infrastructure contains of people, operating practices, negotiated sharing arrangements and all else that are essential for WAMS facilities to provide useful information”.

Nowadays, synchrophasor technology are commercially accessible and are widely used in the power system. Fast scanning rate, high quality phasor measurements of voltage and current and optimal cost communication infrastructure are also well established in the power systems. Therefore, the definition of WAMS is slightly different from past. A general definition of WAMS is as follows:

“The WAMS utilizes the technologies of synchrophasor measurements and conventional measurements with modern communications infrastructure for monitoring the wide area power system and provides the real-time control actions and operations in the power system”.

1.2.2. Components of WAMS

A WAMS obtains widely power system data from conventional and real time measurements, transmits it through communication networks to the control center for monitoring and control actions. Over the last two decades, several arrangements of WAMS have been developed to monitor the wide area power system. There are three major components in WAMS which drives the WAMS towards a more reliable and stable system. Global Positioning System (GPS) is the first key component of the WAMS. It provides very accurate time stamping of the power system measurements which makes GPS possible to calculate the phasors value of the system. PMU uses this time stamping to provide measurements synchronized within one microsecond of each other from different points in wide area network. If GPS signal is lost then PMU provides an indication of this situation, and the corresponding phasor is measured unacceptable and is rejected at the source side.

PMU is the second major component of WAMS and is widely acknowledged as one of the most important achievement in the area of real-time monitoring of the power system. It is a microprocessor based device that uses the concept of digital signal processors to measure the 50/60Hz alternating current waveforms (voltage and currents) at a typical rate of 48 samples/cycle (2400/2880 sample/Sec.) [10]. PMU measure the time synchronized voltage and current phasors of the power system and send that data to the PDC.

PDC is the third major component of the WAMS. It is a node in a system where all the PMUs are directly connected and PDC correlates all the phasor data of the PMUs and fed out as a single stream to the control center for other applications. Apart from the gathering of data from the PMUs, PDC also performs many essential works like, bad data rejection, align the time stamps, a snap shot of phasors and make a coherent recorded data. In some cases, a super PDC is used. A super PDC is also a node in the power system where many PMUs and PDCs are directly connected and it fed out the phasor data in a single stream to the control center for monitoring and control applications.

1.2.3. Architecture of WAMS

WAMS architectures provide a strategy to gather the data from different real time measuring devices and PDCs, and connect this real time data with various data fusion algorithms and methodology to monitor the dynamic changes in the power network. Figure 1.1 shows the architecture of WAMS. It is clear from the figure that PMUs collect the voltage and current values from the system buses and lines respectively, and evaluate real data using advanced signal processing techniques. This information, phasor values of voltage and current is sent to the PDC. Thereafter, PDC collects all the information from the PMUs and fed out as a single stream to the super PDC where many other PDC/PDCs or PMU/PMUs are directly connected. Then Super PDC send that to the control center for real time dynamic monitoring (RTDM), wide area control (WAC) and wide area protection (WAP).

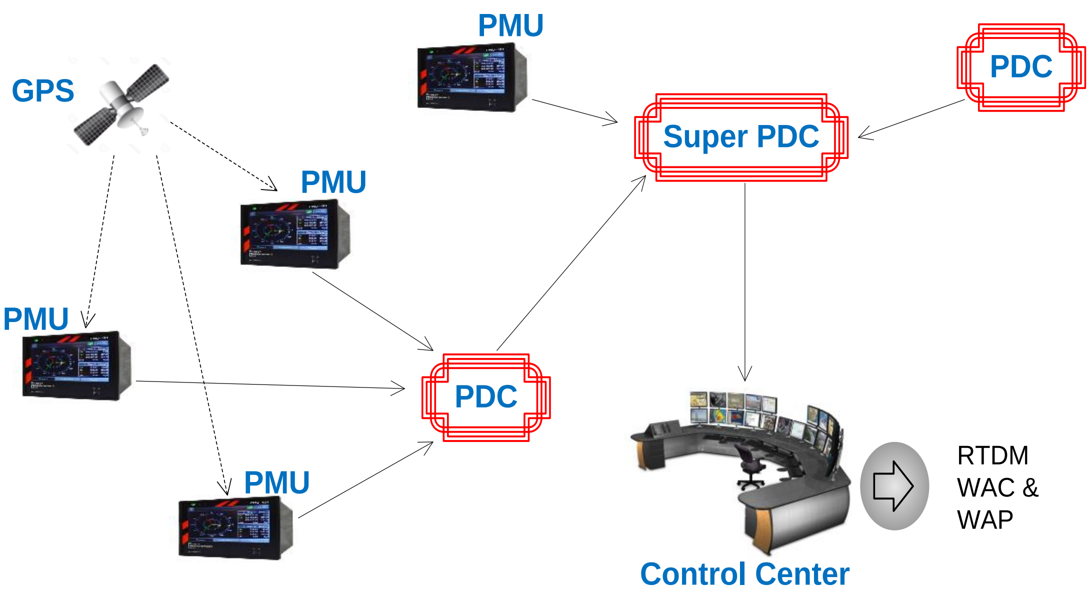

Figure 1.1 Architecture of WAMS

1.3. LITERATURE REVIEW

WAMS applications has been focused around the monitoring, control and adaptive protection of the power system. For wide area monitoring, a set of power system buses have been needed where optimal number of PMUs can be installed. A power network is considered as fully observable when all the states in the power system can either be directly or indirectly observable. Therefore, a proper methodology is needed to find out the optimal locations of PMUs for the full observability of the system. As an application of PMU, assessment of voltage stability has been proposed in this thesis. The field of research pertaining to WAMS application and PMU placement have been of prime concern to the researchers, an overview of relevant works in this discipline has been documented in the subsequent sections.

1.3.1. Optimal PMU placement

Initial work on PMU development and utilization has been reported by *Phadke et al.* [11]–[13]. Several algorithms and techniques have been published in the literature for the optimal PMU placement (OPP) in power system. These techniques for OPP are divided into two parts, conventional and non-conventional techniques as discussed below.

1.3.1.1. Conventional techniques for OPP

The conventional techniques are based on the deterministic algorithm. Therefore, for a particular input, it will always produce the same output. Whereas, more than one solution may exist for the same problem. It is disadvantageous, in some of the problems, where more than one optimal solution is required. Detail introduction of literature based on these techniques are given below.

Baldwin et al. [14] and *Mili et al.* [15] developed an algorithm which finds the minimal set of PMU needed for power system, where the graph theory and simulated annealing methods respectively have been used to achieve the goal. To make the system full observable, only one fourth to one third of the power system buses need to be provided with PMUs [14]. Both the algorithms have taken advantages of the simulated annealing and the graph theory methods in order to optimize the number of PMUs and ensure the observability of the system.

Chen et al. [16] proposed a strategic PMU placement algorithm to improve the bad data processing capability of state estimation. If PMUs are placed judiciously, it is possible to make the entire system observable. In this work, some extra PMUs have been added even though the system was already observable. It has been claimed that extra PMUs will provide increased bad data detection and identification capability. Therefore, it may provide critical data during contingencies and presence of bad data.

Xu et al. [17] developed an optimal placement algorithm for PMUs where conventional measurements such as injection and flows can also be taken into account if they already exist in the system.

Dua et al. [18] proposed a procedure for multi-staging of OPP. This work also proposed two indicators, Bus Observability Index (BOI) and System Observability Redundancy Index (SORI) to improve the quality of PMU placement. Moreover, the concept of maximum observability of the power system using the same number of optimal PMUs has been well-defined in this work.

Aminifar et al. [19] proposed an algorithm using integer linear programming (ILP). This work has been considered for different contingency conditions associated with the power systems. Moreover, communication constraints of the power system has also been considered as measurement limitations and included in the model. *Azizi et al.* [20] proposed a novel equivalent ILP method (EILPM) for the exhaustive search based OPP. In this work, the effect of limited channels of PMU and single contingencies of PMU and line have been included.

Mahaei et al. [21] proposed a Binary Integer Programming (BIP) to solve the optimal PMU problem and maximize the measurement redundancy. Single PMU outage and line outage has been incorporated as a contingency of the system. In this work, authors has considered line outage case as the subset of PMU outage case. Therefore, a single line outage case will not affect the observability of the system if each bus is observable by two PMUs. Besides, multistage OPP problem has also been considered in this work.

Huang et al. [22] presented an ILP model for OPP considering controlled islanding, which also maximize the measurement redundancy by incorporating it in their objective function. The effect of zero injection bus (ZIB) and different contingencies have also been incorporated in this work.

In [23]–[29], a multi-objective function has been developed to calculate the optimal number of PMUs and maximize the measurement redundancy for both normal and contingency cases. However, the contingency case has not been considered in [27]. *Aghaei et al.* [23] proposed the Mixed Integer Linear Programming (MILP) method to solve the OPP problem and Fuzzy decision making has been used to choose the best solution.

Aghaei et al. [24] developed a new multi-objective programming to solve the conflicting attributes and Pareto optimal solutions. A single measurement loss and a line loss case has been considered as the contingency. Besides, minimum distance to ideal point has also been implemented as a new index to select the most desired solution among the available Pareto front based options to achieve judicious choice makers.

Enshaee et al. [25] proposed a Binary ILP methodology for PMU placement. In this work, a new constraints has been developed to add the effect of zero injection buses. Moreover, single PMU outage case, single line outage case and single PMU or single line outage case have also been considered in this work.

Mazhari et al. [26] and *Jamuna et al.* [27] proposed Cellular Learning Automata and biogeography based optimization techniques respectively to find the optimal number of PMUs in the power system. Fuzzy based mechanism from the Pareto optimal solution has been used to select the best solution in [27]. *Esmaili et al.* [28] proposed a mixed integer programming with multi objective function to find out optimal number of PMUs and maximize the observability of the system. Fuzzy memberships have been used to scale the different objective into the same range scale. The main purpose of this scaling has been used to ensure the Pareto optimality of the solution. The presence of ZIB and flow measurement have also been incorporated in [28], [29].

1.3.1.2. Non-conventional techniques for OPP

The non-conventional techniques are based on the stochastic algorithm that generate and use the random variables. Therefore, it may provide more than one solution for the same problem. These techniques can be used to speed-up the process of finding an adequate solution. Some literature based on these techniques for OPP problem have been discussed below.

Genetic Algorithm (GA) has been applied to find out the optimal locations of PMUs by various investigators [30], [31]. *Aminifar et al.* [32] applied a combinations of Immunity algorithm and genetic algorithm for the OPP to improve the algorithm efficiency.

Peng et al. [33] proposed the Tabu Search method for the OPP problem in which augmented incidence matrix has been used for the observability analysis of PMU. A recursive tabu search method has been suggested by *Korres et al.* [34] which claimed superior than multiple Tabu search and higher observability.

Yang et al. [35] proposed a PMU placement problem using the derived posterior Cramér-Rao bound (PCRB) on the state estimation error based on a measurement model which considers the phase angle mismatch from the PMU measurement.

Chakrabarti et al. [36] developed a framework using binary search method for OPP to select the solution resulting in the most preferred pattern of measurement redundancy. Single line outage has been considered as the contingency case. A probabilistic evaluation method of the measurement channels availability for observability analysis is proposed in *Albuquerque et al.* [37].

Ahmadi et al. [38] presented a multi-objective function to minimize the PMU and maximize the measurement redundancy with and without presence of zero injection buses using binary particle swarm optimization (PSO) methodology. Authors ignored the contingency cases for OPP. A modified binary PSO algorithm has been suggested by *Hajian et al.* [39] using improved topological observability rule.

Maji et al. [40] presented the exponential binary particle swarm optimization (EBPSO) algorithm for multiple solutions of optimal PMU placement. In this algorithm, a nonlinear inertia-weight-coefficient has been used to improve the searching capability. *Hurtzen et al.* [41] proposed an iterated local search method to minimize the size of the PMU configuration needed to observe the power system network.

Peng et al. [42] presented a multi-objective problem of PMU placement and used non-dominated sorting differential evolution algorithm based on pareto non-dominated sorting. An unconstrained nonlinear weighted least square algorithm has been developed by *Manousakis et al.* [43] for OPP problem.

Qi et al. [44] proposed an OPP method for dynamic state estimation by maximizing the determinant of the empirical observability Gramian. Load fluctuations and different contingencies in the system have been discussed very effectively. *Aminifar et al.* [45] presented an OPP technique on the basis of the cost/benefit analysis.

Dalali et al. [46] presented a modified binary cuckoo optimization algorithm to find out the optimal locations of PMU in the system. Results have been tested on different networks consist of small test systems to the large test systems. As a contingency case in the system, single PMU outage and single line outage case has been considered.

Pal et al. [47] presented an ILP methodology for such a placement scheme for the dual objective line relay (DULR) while considering realistic costs and practical constraints. Moreover, PMU failure and line outage has been considered and overall cost which contained infrastructure cost, labor cost, cyber security cost etc. have also been minimized using this technique.

Venkatesh et al. [48] and *Sodhi et al.* [49] reported a methodology for the OPP in which only a specific line outage case has been considered. This assumption does not appear to be very sound because the possibility of any other line outage may occur in the system. *Sadanandan et al.* [50] presented a Revised Analytical Hierarchy Process (RAHP) to rank the locations for phase-wise placement of PMUs based on voltage stability monitoring.

Aminzadeh et al. [51] proposed a hybrid optimization technique for OPP by merging abilities of two non-conventional techniques, PSO and Gravitational Search Algorithm (GSA), called as hybrid PSO-GSA. The main focus behind it was the speed-up the performance.

1.3.2. GSA and it's applications to power system

The Gravitational Search Algorithm (GSA) is a novel meta-heuristic search algorithm which is based on the Newton's Law of Gravity and mass interactions [52]. GSA has been reported to be very efficient in solving different optimization problems in power system like Economic Load Dispatch (ELD) [53], [54], reactive power dispatch [55]–[57], optimal location of FACT devices [58]–[60], short term hydrothermal scheduling [61], automatic generation control [62], [63], state estimation [64] etc. In [51], a hybrid PSO-GSA has been reported for the OPP problem. However, OPP problems deal with real numbers. Since OPP problem is a binary search problem, basic concepts of GSA have been modified to incorporate discrete binary search. The resulting algorithm is called BGSA [65]. In the proposed algorithm, agents are considered as objects and their performance is measured by their masses. The heavy masses correspond to good solutions and move slower and conversely light masses correspond to poor solutions and move toward heavy masses much faster [52].

Swan et al. [53] incorporated GSA to solve ELD problem. A comparative study has been carried out between the Evolutionary Programming and GSA method. Finally, GSA method has been provided better results with reduced computational time. Further, *Nath et al.* [54] presented the ELD problem with the incorporation of wind generating system. The results provided the global optimal solution with a high probability for six conventional generators and a wind generator system.

Roy et al. [55] proposed the GSA for solving the multi-objective problem of optimal reactive power dispatch (RPD), which minimize the transmission line loss with proper quality of voltages. This algorithm has been tested on IEEE 57-bus and IEEE 118-bus test systems. Results have been compared with two types of genetic algorithm, four types of PSO algorithm and a seeker optimization method. It has been observed that the proposed GSA converged much faster than other methods. The RPD using GSA has also been applied by *Duman et al.* [56] and *Babu et al.* [57]. The results obtained from the GSA method have provided the improved quality solution in comparison with the results previously reported in the literature.

Sarker et al. [58] applied the GSA to find out the optimal power flow in the presence of multiple Unified Power Flow Controller (UPFC) devices. In this work, results of GSA have been compared with different heuristic search algorithm like, Genetic Algorithm, Stud Genetic Algorithm, Ant Colony Optimization, Probability-Based Incremental Learning and Biogeography-Based Optimization, to show the performance and effectiveness of the proposed search technique, GSA. *Bhattacharyya et al.* [59] and *Packiasudha et al.* [60] also proposed the GSA and cumulative GSA to find out the optimal location of FACT devices to minimize the power system loss.

Nadakuditi et al. [61] proposed a non-dominated sorting disruption-based GSA with mutation concept to find the fixed-head and variable-head short-term hydrothermal scheduling problems. *Khadanga et al.* [62] proposed a "gbest" guided hybrid technique which is the combination of GSA and pattern search optimization method for load frequency control of multi area interconnected power network. The parameters of the controller for each area has been optimized using this novel hybrid technique.

Dahiya et al. [63] has proposed a disrupted oppositional based gravitational search algorithm (DOGSA) tuned sliding mode controller (SMC) for the solution of automatic generation control of interconnected multi-area power network under deregulated environment.

Vedik et al. [64] prepared a GSA in conjunction with weighted least square method to find out the state estimation problem by using the conventional and synchrophasor technology. The results have been shown in this work that the proposed GSA method yield towards the optimum solution and more accurate as compared to other methods.

1.3.3. PMU assisted voltage stability

Power system is critical interdependent infrastructure and, also, it is very important to transmit electrical power from generation end to load end reliably, therefore its performance should be effective. To maintain these features, voltage stability is one of the key areas to maintain the operation of power system within contractual, steady voltage limits before and after any disturbances. The ability to maintain voltage stability is a vital task for a secure and robust power system. Voltage instability occur typically due to low voltage profile, high reactive power loss, poor reactive support in heavily loaded power systems [66]. In recent years, series of blackouts have been encountered in power system. These blackouts have occurred because either of voltage or angle instability or both together was not detected within time and progressive voltage or angle instability further degraded the system condition. Voltage instability which has caused most of those wide area blackouts has become one of global concerns for system operators.

Several methods have been developed to moderate this problem. After development of PMUs the accuracy increased and the calculation time significantly decreased due to high scanning rate and real-time phase angle measurement in spite of employing traditional phasor estimation techniques [67]–[69]. Some of the methods have been suggested in literature to assessment voltage stability using synchrophasor technology, which can be classified into two categories, first is local phasors and second is global phasors. In local phasors, Thevenin impedance based assessment of voltage stability has been incorporated [70]–[76]. Whereas, the use of PMUs to transfer the data are very limited. In global phasors, both monitoring and control action have been done by synchrophasor technology [77]–[80].

Gong et al. [70] proposed a method to predict the steady-state voltage stability limit in power system while taking into account three types of maximum transferable powers (real power, reactive power and apperent powers). PMU based Voltage Stability Index (VSI) is defined as the minimum of the three margins. For a large power system, a method has been developed to simplify the large system. The proposed VSI provides the voltage stability margine of each load bus and identifies the load bus that is the most closer to its marginal voltage operating point.

Corsi et al. [71] presented the enlarge understanding on the shape of the nose curve of power-voltage (PV) curve. The authors have shown that the local control loops are powerfully involved and modify the shape of the nose curve in the voltage stability phenomenon. The main focus of this work on the new opportunities to estimate the proximity to voltage instability provided by a synchrophasor measurement.

Larsson et al. [72] presented a new method for assesment of voltage stability of transmission corridors. In this work, several lines have been grouped into a socalled virtual transmission corridor and there parameters have been calculated using wide area measurement system.

Mesgarnejad et al. [73] presented a systematic approach for comparing the voltage stability indices using PMUs, where the behavior of different indices to a step load change, for studying long term voltage stability, has been compared. The comparison has been carried out in two methodologies. First, accuracy and preciseness of each index and second, effect of error in phase angle measurement.

Rehtanz et al. [74] proposed a system design based on synchrophasor technology, encouraging power system protection schemes for frequency, voltage instability and small signal angle. The main focus of this work lies on the application for emergency voltage stability control. Moreover, a special algorithm has been introduced using the dynamic view for cascaded outages together with long-term voltage instability.

Corsi et al. [75] proposed a new voltage instability risk indicator based on local phasor measurement unit at high scanning rate. The main contribution of this work is the novel algorithm utilized on the real-time adaptive identification of the Thevenin voltage and impedance equivalents. Whereas, the risk criterion is based on the real-time computation of the Thevenin equivalent impedance of the classic electrical circuit.

Chen et al. [76] presented an uncertainty quantification method for PMUs in voltage instability prediction. In this work, Thevenin equivalent impedance has been used for voltage stability assessment. The results have been further applied to specify the accuracy requirements for synchrophasor measurements in voltage stability analysis.

Milosevic et al. [77] presented a novel concept for local monitoring for voltage instability and emergency control in presence of voltage-sensitive loads which are provided by PMUs. The algorithm of this work has suggested the control actions to be used when the stability margin is minor and the reactive power reserves are almost exhausted.

Glavic et al. [78], [79] presented an early detection of voltage instability from the system states provided by PMUs. After detection of voltage instability, method of this work fits a set of algebraic equations to the sampled states and achieves an effective sensitivity in order to identify when a combination of load powers has passed through a maximum. This work has considered sensitivities of reactive power generation to reactive power loads. In second part of this work, results have been obtained from detailed time-domain simulation of the Nordic32 test system, without and with measurement noise, respectively.

Haque et al. [80] proposed a very simple method to determine the maximum loading point and voltage stability margin of the power system. The required data could be obtained either from load flow analysis or from sysnchrophasor technology in power system. A simple computaion has been used therefore method has a very high potential for on-line application.

The algorithm proposed in Glavic et al. [78], [79] has been further extended in [81] for the voltage stability of power system. In this work, load shedding scheme has been proposed, which is adaptive in terms of the amount of load to be shed. When the sensitivities change sign, a snapshot of all the transmission voltage is taken in the area of interest and load shedding controller is made operative until all voltages recover to a value higher than their respective acceptable threshold values.

Apart from the different voltage stability methods based on fundamental circuit laws (Thevenin theorem, Tellegen's theorem etc.), artificial intelligence based voltage stability assessment methods utilizing synchrophasor measurements have also been suggested in the literature cited in [82]–[85].

Zhou et al. [82] proposed an artificial neural network (ANN) based methodology for assessment of long term voltage stability margine under normal and N-1 contingency situation. Data obtained are in real time using PMUs. The bus voltage magnitudes and the phase angles have been taken as the inputs to the Multi-Layer Perceptron networks.

Mani et al. [83] developed a voltage stability margin tool using a combination of the reactive power and voltage stability of the power system. A set of Multi Linear Regression Models (MLRM) has been developed to cover all possible loading of the system situations and contingencies. Moreover, neural network has been developed for the selection of a MLRM in real time at all the measureing instant. For this, PMUs have been provided the voltage phasors and angles of the buses of the power system.

Zhao et al. [84] proposed an effective methodology to estimate the voltage stability margin in real time using a local PMU. An artificial neural network has been incorporated to estimate the regional margin. In this work, radial basis function neural networks (RBFNN) has been trained using off-line results to estimate the voltage stability margin. All the voltage phasors of the critical buses and current phasors of the critical lines have been collected as an inputs for training the neural network. The proposed work provided the local areas threaten by voltage instability and then monitored online.

Shah et al. [85] presented a fast assessment of voltage instability in power system using PMU and ANN based approach. Neural network has been trained in different contigencies using the outputs of PMUs.

1.4. OBJECTIVE AND SCOPE OF THE THESIS

The main objective of this thesis is to develop an algorithm to optimize the number of PMUs and maximize the observability of the power system. Therefore, in the formulation of problem objective, two objectives have been incorporated. First objective is to optimize the number of PMUs in the system and second objective is to maximize the observability of the system. Thus the PMU placement problem has been expressed as a multi-objective problem. The effect of presence of zero injection buses (ZIB) has also been incorporated in this work. Besides, single PMU outage and single line outage cases in the presence of zero injection buses have been investigated as a contingency. Which of the above contingencies has occurred may not be known a priory. This necessitates formulation of the PMU placement problem such that none of the buses is left unobservable in such uncertainty. The case of uncertainty of PMUs has not been taken proper attention in the literature. Therefore, the PMU and line outages have been dealt with separately in this work.

Most of the techniques mentioned in previous sections discriminate optimal location of PMUs in the system but do not include the suitable consideration of communication infrastructure in the OPP problem. As a second foremost objective of this thesis, a WAMS installation cost minimization and observability have been reported in this work. For this, a novel multi-objective function has been proposed. Different contingency cases have also been included to improve the reliability of the system. Besides, the effects of presence of preinstalled PMUs have been considered.

Besides getting the maximum observability of the power system, a real-time assessment methodology of voltage stability using Phasor Measurement has been presented. PMUs are placed at strategically obtained location such that minimum number of PMU's can make all the buses observable with maximum observability. Data obtained by PMU's are used for voltage stability assessment with the help of successive change in the angle of bus voltage with respect to incremental load, which is used as on-line voltage stability predictor.

1.5. ORGANIZATION OF THE THESIS

This thesis is organized in six chapters. The present '**Chapter 1**' deals with the basic concepts of the power system, need of monitoring of the system and the fundamentals of the WAMS. This chapter also presents the essential literature survey of the research carried out in the area of optimal PMU placement (OPP) and voltage stability and sets the objective for the present work.

Chapter 2 describes the PMU technology and its fundamentals. Comparison between SCADA system and PMU is discussed and also PMU standards is given. PMUs are used for both online and offline applications in power system. Some of the applications of PMUs in power system are described in this chapter. Further the voltage instability has been discussed elaborately as a special case for which the application of PMU placement has been illustrated in this thesis.

Chapter 3 presents the basic formulation of optimal PMU placement. The concept of observability of the system is also explained. Besides this chapter proposes the Binary Gravitational Search Algorithm which is applied in this research to optimize the number of PMUs and maximize the observability of the system. The proposed formulation is implemented on MATLAB platform.

In **Chapter 4**, a novel multi-objective OPP methodology is presented to optimize the number of PMUs and maximize the observability of the system. Therefore, in the formulation of problem objective, two objectives have been incorporated. Further to show the effectiveness of the proposed methodology different contingencies are taken. The proposed method is demonstrated on IEEE 14-bus, -30-bus, -118-bus, Northern Regional Power Grid 246-bus Indian system, and Polish 2383-bus system.

Chapter 5 presents the communicating infrastructure based optimal PMU placement by using a new multi-objective function. This chapter basically finds the optimal PMU placement including the minimum paths of communication infrastructure. Therefore, overall cost of installation of PMUs in WAMS has been reduced. The proposed method is demonstrated on IEEE 14-bus, -30-bus and -118-bus test systems.

Chapter 6 proposes voltage stability monitoring index using phasor measurement units to prevent from the collapse of the system. Data obtained by PMU's are used for voltage stability assessment with the help of successive change in the angle of slope of the bus voltage with respect to incremental load, which is used as voltage stability predictor. The proposed method is demonstrated on IEEE 14-bus, -30-bus and -118-bus test systems.

Chapter 7 concludes with the summary of contributions of the thesis with scope for further work in this new area of specialization. A comprehensive bibliography of documented literature on this topic of research is given in references.