A Systematic Literature Review of Optimal Load Shedding Models

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Abstract— ***This paper details a systematic literature review concerning optimization techniques for load shedding modelling. Emphasis is given on reporting similarities and differences among different model keeping in review minimum requirement, class of optimization methods, and solution techniques. A generic framework for optimization load shedding model building is also described.***

Keywords— ***systematic literature review; optimization techniques; load shedding modelling; requirement; generic framework***

I. INTRODUCTION

Load shedding is occurred by the deliberate shutdown of electric power in parts of a power distribution network to prevent the failure of the entire system when demand exceeds supply. On the contrary, if supply exceeds demand and load is not properly distributed through the supply lines it results into a power loss. Thus, effective measures should be taken to prevent the catastrophic situation.

This power loss exhibits rolling blackouts and brownouts. Electric supply companies use rolling blackouts to avoid a total shutdown of the power system, whereas a brownout is an intentional or unintentional drop in voltage in an electrical power supply system. Intentional brownouts are used for load reduction in an emergency [1].

If insufficient generation is provided to the consumers by the power grid, then both the power system frequency and the rotating speed of generator will drop to a lower level, and even exceed the allowable limit, which has bad impacts on the system stability. These disturbances create a generation deficit that can damage the entire system. Power generation play a vital role in preserving the stability of the system during turbulences, which may result into a power generation deficit. There are two types of generation deficits; generation redispatch that is covered by redispatching of remaining generators, and the other is load shedding such deficit is balanced by setting frequency steps to shed load blocks [2].

Load shedding is one of the major problem of South Asia, and have total production of 1211 TWh[1]. Total production of electricity in Pakistan is 97.8 TWh, whereas in India, Bangladesh, Nepal and Sri Lanka is 1052 TWh, 47.3 TWh, 3.5 TWh, 11.3 TWh respectively. Pakistan has 78.89 TWh average consumption of electricity, while India, Bangladesh, Nepal and Sri Lanka have 864 TWh, 41.52, 3.23 TWh, 10.17 TWh respectively. A detailed statistics of this region is given in Table I, from which it can be understood that despite of having a large population this region is inept to produce enough electricity to cope with requirements for its population. The reasons are lack of resources, low GDP as compared to population, mismanagement of power systems, and corruption. Although, tariff of these countries are less as compared to the developed countries. This shortfall is creating devastating effects on the economy, industrial sector, educational sector and psyche of people [3], along with long load shedding hours [4].

One of the ways to diminish load shedding is through load curtailment i.e. a way to balance electricity supply and demand by controlling consumption patterns. Other way is through load balancing that refers to the use of various techniques by electrical power stations to store excess electrical power during low demand periods for release as demand rises.

This paper is aimed at collecting literature on optimization models that tackle load shedding problem. Here our focus is to critically analyze these models with an aim to collect advantages and disadvantages eminently each model has to offer. In order to compare these models we need a criterion. We delved into literature to find such a criterion, but there is no single agreed upon criterion to evaluate optimization models. Therefore we collected factors that influence the suitability of a certain model. This will help in future research where one ought to develop a new load shedding model with better performance guarantee.

This paper is organized as follows. Section II describes the methodology of optimization models and load shedding model's requirements, while Section III deals with discussion. Conclusions and perspectives are presented in Section IV.

[1] Combined production of Pakistan, India, Bangladesh, Nepal and Sri Lanka.

TABLE I. POWER STATISTICS OF SOUTH ASIA

	Pakistan	India	Bangladesh	Nepal	Sri Lanka
GDP [5]	$289 billion	$2.29 trillion	$223 billion	$67 billion	$80 billion
Population [6]	199 million	1.25 billion	168 million	28 million	22 million
Total production of electricity [5]	97.8 TWh	1052 TWh	47.3 TWh	3.5 TWh	11.3 TWh
Installed Electricity Generation Capacity	24 GW	301 GW	10 GW	782 MW	3.9 GW
Share of population with access to electricity [7]	73%	81%	61%	76%	94%
Average power per capita (watts per person) [5]	67	152	28	N/A	N/A
Average Consumption [5]	78.89 TWh	864 TWh	41.52 TWh	3.23 TWh	10.17 TWh
Average Demand	17 GW	164 GW	8.5 GW	1291 MW	N/A
Shortfall	5 GW–6 GW	N/A	1 GW	585 MW	N/A
Electricity tariff rates for 0-100 unit residential(Rs[2]./kWh) [8]	KESC: 4.42 WAPDA: 4.05 (above 100 units: 5.00)	West Bengal: 2.91 rural, 2.92 urban CESC: 4.5 urban	2.76 (up to 75 unit: 2.49)	5.09 (50 unit: 6.00)	2.91 (90 unit: 9.93)

II. Methodology

This section details methodology adopted to create a systematic review. In first subsection, we describe the theoretical framework adopted for systematic literature review. Second subsection describes optimization model to tackle load shedding problem. Third subsection describes evaluation criteria for the comparison of different optimization models as described in literature.

A. Review Methodology

In this paper, the methodology proposed by Kitchenham et al. [9] for a systematic literature review (SLR) is adopted. Although, this methodology is developed for systematic literature review for software engineering but the proposed methodology is general, and can be used for systematic review for engineering literature.

First of all, a systematic literature review is a means of identifying, evaluating and interpreting all available research relevant to a particular research question, or topic area, or phenomenon of interest [10]. The most common reasons to commence a SLR is; to summarize the existing evidence concerning a treatment or technology (e.g. to summarize the empirical evidence of the benefits and limitations of a specific agile method), and to provide a framework or background in order to appropriately position new research activities.

For the sake of completeness, at this juncture we describe four main points of Kitchenham methodology:

1. Research questions
2. Search process
3. Inclusion and exclusion criteria
4. Quality assessment

Specifying the research questions is the most important part of any systematic review i.e. by assessing the development and effect of a model, and by identifying the impact of a model on reliability, performance and cost. The search process identifies primary studies[3] that address the research questions. Inclusion/exclusion criteria deal with the re-evaluation and re-testing of the primary studies. In addition to inclusion/exclusion criteria, it is considered critical to assess the quality of primary studies by providing an explanation for differences in a study, and our study is based on these points.

B. Optimization Models

The problem of load shedding was first reviewed by the Operating Committee of the Northwest Power Pool in 1950, which presented the principles for operation during pool disturbances of breakups that were later discussed by Swanson [11]. A scheme to drop automatically all synchronous loads in distress areas to reduce system loads by further reducing the system voltage by the use of frequency relay was mentioned. This scheme had no primary effect upon the extent of outages caused by multiple failures on the transmission system, but was of material aid in reducing the duration and severity of secondary involvements caused by sustained low voltage and low frequency.

A systematic approach toward minimizing the curtailment of service in a power system after a severe fault was discussed by Hajdu [12]. The problem of minimizing load curtailment under a given set of emergency conditions was formulated. First, a feasible steady state solution was obtained for the post fault network configuration. Then, starting from this initial feasible solution, the minimum curtailment was approached by a gradient technique. The proposed computational procedure was based on the Newton Raphson technique for solving the power flow equations, and the Kuhn Tucker theorem for the optimization. Also, reactive power and frequency variations were not considered in the analysis.

[2] Pakistani Rupees

[3] A study investigating a specific research question.

El-Abiad [13] presented a general formulation of the economic dispatch problem that was based on the Lagrange multipliers approach. The necessary optimality conditions were established and upon these conditions an algorithm was developed for real power and voltage magnitude dispatch i.e. reactive power dispatch. Feasible solutions were attained through optimization procedure. Lagrangian multipliers were calculated through iterative procedure, but once the optimal solution is attained within a specified precision the additional dual variables of the Kuhn Tucker theorem for the effective inequality constraints can be calculated.

A model for sensitivity in power systems was presented by Subramanian [14], which uses it in conjunction with linear programming for the solution of load shedding problems with a minimum loss of loads. A weighted error criterion was used to take priority schedule into account so that it could be either a linear or a quadratic function of the errors. These error criteria are advantageous because the importance of the schedule could be maintained even if some loads are very small. The percentage error criterion magnifies the load loss for bus having small loads. The partial square root method was used for the solution algorithm, which reduces the number of multiplications needed.

The problem of rescheduling generators and shedding loads in an emergency state as a nonlinear optimization problem that was formulated by Chan [15]. The desired solution was a set of control actions which, when applied, removes all the constraint violations such as abnormal voltages and line overloads with a minimum of rescheduling and load shedding. The nonlinear problem was approximated by an accurate sensitivity model which takes into account real and reactive nodal injections, voltage angles and magnitudes, and loads' sensitivity to voltage magnitudes. An upper bounding, sparse, linear programming algorithm was used to solve the linearized scheduling problem. However, it does not consider the system’s frequency and it can be applied to eliminate overloads in the equipment.

Palaniswamy [2] presented a method for optimal load curtailment in a power system taking into account generator control effects and voltage and frequency characteristics of loads. The optimization problem was solved by a second order gradient technique, which reduced the computational time. The method takes account of generator control effects and the voltage and frequency characteristics of loads. The proposed modeling does not deliver a net load shedding and the power balance is obtained through load and generation variations with frequency, which can be insufficient.

Above mentioned optimization models were analyzed for load shedding corresponding to static models. Succeeding literature review is on dynamic modeling. Rudnick [16] formulated the load shedding problem as a nonlinear optimization model that was solved through the Damped Lagrangian Penalty algorithm. The load was modelled considering its voltage frequency characteristic, reflecting the dampening character of the load.

Shokooh et al. [17] demonstrated the need for a modern load shedding and introduced the new technology of intelligent load shedding. Comparisons of intelligent load shedding with conventional load shedding methods were made. The authors argued that conventional methods of system load shedding are too slow and do not effectively calculate the correct amount of load to be shed. This results in either excessive or insufficient load reduction.

TABLE II. OPTIMIZATION AND SOLUTION TECHNIQUES

Author	**Optimization Model**	**Solution Techniques**
Hajdu [12]	LP	Newton Raphson method, Kuhn Tucker theorem
Subramanian [14]	NLP	Partial square root method
Chan [15]	NLP	Sensitivity model, Upper bounding technique, Sparse linear programming technique
Medicherla [18]	LP	Newton Raphson method, Decoupled load flow model
Palaniswamy [2]	NLP	Second order gradient technique
Abidi [19]	NLP	Local load shedding scheme
Rudnick [16]	NLP	Damped Lagrangian penalty algorithm
Xu [20]	NLP	Dynamic model for load shedding, Static model for load shedding, Discretization method
Shokooh et al. [17]	---	Intelligent load shedding model
Malekpour [21]	NLP	Continuous constriction factor particle swarm optimization (CPSO), Genetic algorithm (GA)
Wu [22]	NLP	Frequency response model, Under frequency load shedding scheme
Koutsopoulos [23]	NLP	Demand load control policies
Alamaniotis [24]	LP	Kernel based Gaussian processes, Pareto optimal theory
Fin Lin [25]	MINLP	Alternating direction method of multipliers (ADMM)

An approach of the continuous constriction factor particle swarm optimization (CPSO) technique was developed by Malekpour [21] to overcome load shedding, which considers continuous modeling of power system load and the original power factor of each transmission load bus after load shedding. The problem was formulated to minimize the sum of curtailed load in contingency situations and restore the power system to its normal security and operation conditions. The penalty function approach was also addressed to reduce the number of infeasible solutions that appear in the subsequent iterations. Although, the results were appealing but model was not complete as it didn’t contemplated frequency of the system.

A mixed-integer nonlinear program (MINLP) was used by Fin Lin [11] to solve power flow equations. The optimal load shedding problem was formulated, which contained binary decision variables and nonlinear AC power flow constraints. This indicated that the problem had a separable structure meaning all decision variables are separable except for the coupling nonlinear power flow constraints. This problem was further exploited to develop an approach based on the alternating direction method of multipliers (ADMM). Also, frequency deviation and reactive power were not considered in the model which may affect the results.

Aforementioned reviews indicate that an accurate optimization model must be presented in order to tackle a load shedding problem.

In Table II, we have summarized models described above. The table describe model type in the framework of mathematical optimization along with solution technique adopted. Fig. 1 illustrates a generic optimization model. The model includes objective function and constraints that are in essence with the basic requirement to create optimization model, and are discussed in Section III.

C. Model Evaluation Criteria

To compare different load shedding optimization models one need a criterion. Unfortunately, there is no single agreed upon criteria found in literature that can evaluate each model. Thus we direct our attention towards a collection of minimum requirements that a load shedding optimization must meet.

The requirements while designing a load shedding model for optimization are that active reactive and power, voltage, frequency, current, and impedance are integral part of an electrical power system [16]. All of these variables must be considered for minimizing load shedding otherwise optimal results cannot be obtained.

Power flow and power balance equations must be included in the model while power factor must be constant till the result, which simplifies modeling and reduces the variables. Load must be dependent on voltage and frequency. Model must deliver a net load shedding, and it must minimize the non-served energy and service degradation with respect to network constraints and operation constraints that are governed by above mentioned variables for the desired results.

It is to be noted that if voltage frequency characteristic of the load is not taken into interpretation, it would need more iterations due to the saturation of the limit constraints thus the solution would be more difficult to search. So, the model is unpretentious. Also, resulting into an excessive load shedding that is of the same order as the generation deficit. Instead, when considering the voltage frequency characteristic of the load, the power deficit is partly dissipated by the load variation with voltage and frequency; few limit constraints are saturated and the shed load is less for an equal power deficit. Furthermore, considering the active and reactive power of the load as independent variables implies results with no reactive load shedding, and that is not in accordance with the reality. It also infers cumulating the number of variables of the problem and the solution times. And, if the dependence between the active and reactive powers of the load are not taken into account then the results will not agree with the real systems. Also, if in the load modeling there is no consideration given to the voltage frequency characteristic then there will be an excessive load shedding, this will result into a model with less variables.

III. DISSCUSSION

Techniques based on the concept of Lagrangian multipliers are widely used in this area of research. Recently, the shift of this area is towards heuristic search techniques such as Genetic Algorithm (GA) [21], Particle Swarm Optimization (PSO) [21], stochastic algorithms [23] and [24].The major reason of this area shift is because heuristic search techniques can solve problem of large bus system.

TABLE III. INCLUSION/EXCLUSION CRITERIA OF MODELS

Model Requirements	**Models that follows**
Inclusion of power flow equations	Palaniswamy [2], Hajdu [12], El-Abiad [13], Chan [15], Rudnick [16], Medicherla [18], Xu [20], Malekpour [21], Fin Lin [11], Wang [26], Shah [27], Berg [28]
Exclusion of frequency	Hajdu [12], El-Abiad [13], Subramanian [14], Chan [15], Medicherla [18], Abidi [19], Malekpour [21], Koutsopoulos [23], Alamaniotis [24], Fin Lin [11], Shah [27]
Exclusion of reactive power	Hajdu [12], Abidi [19], Wu [22], Wang [18], Alamaniotis [16], Fin Lin [11], Shah [27]
Exclusion of active power	Abidi [19], Alamaniotis [24], Wang [26]

Load shedding based techniques were also developed [11], [17], [19] and [22]. An effective local load shedding (LLS) scheme was developed by Abidi [19], which alleviated equipment overloads in underground transmission networks. This scheme depended upon the severity of overloads, where accuracy and speed are traded for these overloads. This scheme is effective, as it selects the load to be shed by priority levels, while spreading the amounts over as many substations. Drawback of this scheme is that its model only considers the active power while excluding reactive power whereas defying the criteria of model evaluation, and the load is modeled as constant power which reduces the effectiveness of the results.

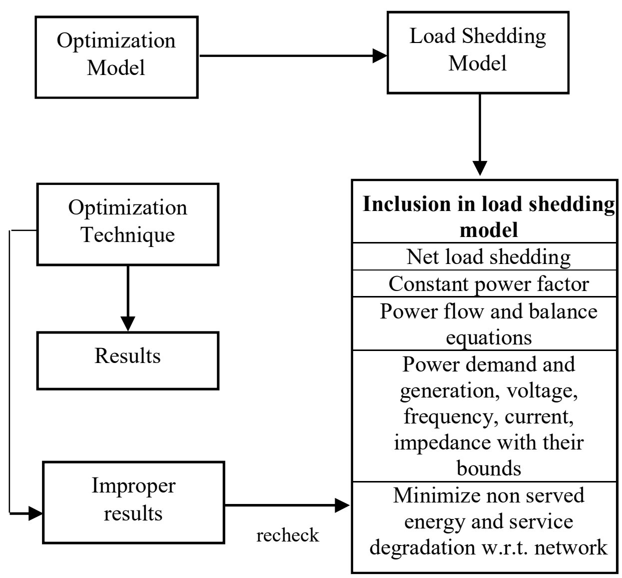

Figure 1. Generic Optimal Load Shedding Model

Another improved load shedding scheme was introduced by Shokooh et al. [17]. This scheme uses a technology i.e. intelligent load shedding (ILS) which combines system online data, equipment ratings, user-defined control parameters, a knowledge base obtained from offline system simulations, system dependencies, and continually updated dynamic load shedding tables.

Hajdu [12] was unable to give an incentive on the problem of transient stability, apart from the fact that load shedding is one of the important control inputs affecting the stability properties of a post fault system. The article [13] was intended generally for the presentation of the method of solution rather than the interpretation of dual variables and mathematical formulation. Alike Hajdu, transient conditions were not considered in [14]. Also, the optimization neither considers the operational requirements nor the frequency of the system. This approach did not guarantee to converge to an optimal solution of the nonconvex problem.

For further developments in this field Rudnick [16] advised to develop optimization methodologies with continuous and discrete or mixed variables, and to make a more complete, detailed and accurate modeling of the loads in each of the bus to adequately escalate their behavior. Decades later, Fin Lin [25] implemented methodology advised by Rudnick [16] but excluded frequency deviation and reactive power from the model. Still a model with this approach satisfying all the model requirements is yet to be developed.

Table III shows the suitable requirements that displays a significant part in the development of a load model. It can be concluded from the table that all the models excluded a requirement except Rudnick's model fulfils all the requirements, and can be used for optimization.

TABLE IV. OPTIMIZATION PARADIGMS' ANALOGY

Optimization Paradigms	**Authors**
Linear programming	Hajdu [12], Medicherla [18], Alamaniotis [24], Berg [28]
Nonlinear programming	Palaniswamy [2], El-Abiad [13], Subramanian [14], Chan [15], Rudnick [16], Abidi [19], Xu [20], Wang [18], Malekpour [21], Wu [22], Koutsopoulos [23], Fin Lin [25], Wang [26], Shah [27]
Mixed integer nonlinear programming	Fin Lin [25]
Multi objective optimization	Palaniswamy [2], Hajdu [12], El-Abiad [13], Chan [15], Rudnick [16], Xu [19], Malekpour [21], Alamaniotis [24]
Static models	Palaniswamy [2], Hajdu [2], El-Abiad [13], Subramanian [14], Berg [14], Chan [15], Medicherla [18], Abidi [17], Wang [26], Shah [27], Berg [28]
Dynamic models	Rudnick [16], Xu [20], Malekpour [21], Wu [22], Koutsopoulos [23], Alamaniotis [24], Fin Lin [25]

Optimization paradigms and solution techniques of different articles are represented in Table IV and Table V respectively. Solution techniques to minimize load shedding are initiated in order to relieve system overload and correct the declining system voltage. With the numerous developments in this area for the purpose of finding optimized load shedding amount signifies its importance for the stable and reliable power system operations globally.

Finally, all optimization techniques have its pros and cons. Nonetheless, the implementation of these strategies can decrease the prospect of power system problems and improve the dependability of energy system. On the other hand, further development of such techniques is essential for feasible practical use appropriate for online as well as real-time applications.

TABLE V. SOLUTION TECHNIQUES' ANALOGY

Solution Techniques	**Authors**
Load shedding schemes	Swanson [11], Shokooh et al. [17], Abidi [19], Wu [22]
Classical optimization	Palaniswamy [2], Hajdu [12], El-Abiad [13], Subramanian [14], Chan [15], Rudnick [16], Medicherla [18], Xu [20], Fin Lin [25], Berg [28]
Heuristic search	Malekpour [21], Shah [27]
Stochastic approach	Koutsopoulos [23], Alamaniotis [24]

IV. CONCLUSION

In this paper, an overview of study in the field of optimal load shedding of power systems is presented. These requirements are collected by adopting a systematic literature review procedure as proposed by Kitchenham and is known to play a vital role in usefulness of models. An inventory of optimization models is presented highlighting the significant differences and similarities of these models. A generic framework for creating an optimization model for load shedding problem is also presented.

In future, our goal is to analyze the suitability of these models in the context of load shedding problem in Pakistan. Adoption of these models to Pakistan scenario is expected to assume a level of difficulty due to differences in infrastructure and generation facilities as compared with the countries for which the reported models were developed.

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