An Efficient Cost-Effective Experimental Approach for Intelligent Load-Shedding: A Case Study

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Abstract- The problem of power shortfalls in Pakistan has had a severe impact on industrial and agricultural growth in the country. Furthermore, they affect how people there go about their daily lives. This paper presents a novel experimental load shedding strategy for solving the existing power grid issues. The proposed method works using the existing programmable logic control (PLC) system and applies an intelligent approach experimentally by adding few devices. As a case study, the proposed load shedding scheme has been applied and tested to the Peshawar Electricity Supply Company (PESCO). The proposed method outperformed the existing load shedding scheme in terms of minimizing the load shedding time with the least economic impact. The proposed system also has a cost-effective design based on the existing grid infrastructure with minimal system upgrade requirements.

Keywords Load shedding, power quality, programmable logic control (PLC), SCADA.

Nomenclature

AI	Artificial Intelligence
AMR	Automatic Meter-Reading
AMI	Advanced Metering Infrastructure
ANFS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
CB	Circuit Breaker
DISCOs	Distribution Companies
FLC	Fuzzy Logic Control
GA	Genetic Algorithm
GSM	Global System for Mobile Communications
GSS	Grid Sub-Station
IPPs	Independent Power Producers
KESC	Karachi Electric Supply Corporation
PDC	Power Distribution Center
PESCO	Peshawar Electricity Supply Company
PEPCO	Pakistan Electric Power Company
PLC	Programmable Logic Control
PSO	Particle Swarm Optimization
SMS	Short Message Service
WAPDA	Water and Power Development Authority

1. Introduction

In the last decade, several major blackouts around the globe have resulted in severe financial losses and disrupted customer comfort. System blackouts can be avoided through implementing proper control strategies by considering contingency analysis to maintain the balance between supply and demand in case of system disturbances. A sudden change in power system operation, such as the loss of generation units, high-voltage transmission line outages, a malfunction in the operation of protective relaying, or a sudden increase in demand can result in a large imbalance between supply and demand within the power system. This causes the system to operate beyond its operating constraints, such as the permissible voltage and frequency operating limits. As a result, the power system becomes unstable. The system's operators will apply emergency operation control strategies to restore the system's stability. Load shedding is considered the last option to be applied to avoid cascaded trapping and system blackout. Load shedding can be defined simply as a coordinated set of actions to reduce the power demand in order to match the available supply. It should be applied rapidly and selectively to restore the balance of the power system and maintain stability.

Over the last 30 years, the problem with Pakistan's power grid has been that there is not enough generation capacity to meet the demand at all times. This shortage of electricity has continually stalled the progress of Pakistanis in every aspect of life and affected industrial and agricultural growth, which in turn has affected the country's economy. Load shedding is done to balance power demand and supply, which has forced industries and businesses either to close or relocate to other parts of the world [1]. To address this shortage of supply, several options are under consideration, such as increasing generation capacity, the development of emerging renewable energy technologies, and power system optimization. Meanwhile, there are great efforts towards the suitable and efficient implementation of improved load shedding strategies that reduce the severe impacts of power shortages on both the economy and human comforts.

In Pakistan, electricity production is provided by two vertically integrated power utilities, namely the Water and Power Development Authority (WAPDA) and the Karachi Electric Supply Corporation (KESC). While WAPDA operates in all of Pakistan except Karachi, KESC operates only in the city of Karachi and its surrounding areas. Power generation in Pakistan is delivered by 42 independent power producers (IPPs) with an installed generation capacity of almost 34 GW in 2019. Since September 2007, WAPDA has been divided into two distinct entities: WAPDA and Pakistan Electric Power Company (PEPCO). WAPDA takes care of water and hydropower development, while PEPCO is responsible for thermal power generation, transmission, distribution, and billing services. There are 11 power distribution companies (DISCOs) working under PEPCO, and their responsibilities are to distribute electricity to customers within allocated regions.

The problem of load shedding has been investigated by many researchers and discussed widely in the literature. Different solutions have been proposed based on various aspects, including system requirements, constraints, operation times, system stability, and economics. The main concern has been to restore system equilibrium between supply and demand at an optimum load shed. In developing countries such as Pakistan, the problem of supply shortage versus demand has forced power distribution load centers to apply load shedding to maintain system stability and avoid system collapse, which might lead to severe blackouts. Hence, there is an urgent need for initiatives and proposed practical algorithms to make the process of load shedding more efficient based on system infrastructure. There have been continuous efforts by authorities and researchers in Pakistan to investigate this problem and find solutions. The Islamabad Chamber of Commerce and Industries conducted research to identify the reasons for the shortfall in electricity from the perspective of generation, transmission, and distribution, which eventually results in load shedding and directly affects the commerce and industries of the country, as noted in [1]. The performance of all DISCOs is monitored continuously by PEPCO. In [2], the authors proposed an intelligent assessment framework of Renewable Energy security issues in PAKISTAN with focus to overcome the problems of load shedding . K. Ulla [3] explained in detail the electricity infrastructure in Pakistan, suggested some future system modifications to be undertaken, and proposed solutions to be applied to reduce the load shedding dilemma in Pakistan. To avoid voltage collapse and system blackout, the concept of under-voltage load shedding has been applied [4]. An approach for under-voltage load shedding using particle swarm optimization was presented in [5]; the concept of dynamic security-constrained OPF was implemented to develop in the model. Rudez and Mihalic performed an analysis of under-frequency load shedding using a frequency gradient [6]. The purpose was to investigate the factors that influence the gradient. A novel load shedding algorithm for power plants has also been proposed [7]. The algorithm uses a combination of the information provided by the measurement of the frequency with the available information on the status of the generators. A new distributed load-shedding scheme for agent-based autonomous operation of a microgrid is intdoduced [8]. Kaffashan et al. developed a robust under-voltage load shedding scheme against voltage stability [9]. An adaptive load shedding method for enhancing the frequency stability in microgrids was also introduced by Marzband et al [10]. Tahir et al. applied an artificial neural network for optimal scheduling of electrical power in energy-deficient scenarios [11]. A new under-frequency load shedding technique that works on a combination of fixed and random priorities of loads for smart power grid applications is suggested in [12].

This paper presents a novel load shedding strategy to solve the existing issues with Pakistan's power grid. As a case study, the proposed strategy has been applied to the Peshawar Electricity Supply Company (PESCO); the current scheme used is quite outdated. PESCO's load shedding schemes do not possess any constant remote monitoring nor controlling infrastructure and protocols to govern them. Different infrastructures for remote load shedding and their drawbacks were identified in detail by the researchers in [3] and [13] for the purpose of devising a new system for PESCO. When applying load shedding remotely, equipment such as automatic meter reading (AMR) meters, transceivers, and repeaters were implemented. Automated metering infrastructure serves as the backbone of these techniques, and different researchers have discussed how these different technologies can be used in reference to advanced metering infrastructure (AMI) for communication. The pros and cons of different technologies, such as fixed networks, radio frequency networks, power line communication, and wireless fidelity (Wi-Fi) compared to AMI have been presented by researchers [14] and [15], but the existing communication technique and its range of access had to be considered by keeping PESCO's geographical area in mind.

The key motivation for conducting this research work is to upgrade the existing infrastructure of the PESCO for minimizing the load shedding time and enhancing the economic impact. The upgrade of the existing infrastructure is a cost-effective solution as compared to new installations. With the modified intelligent load shedding scheme, the main objectives of the research are: a shorter response time for load shedding, improve system recoveries at minimum loss and maximizing revenues.

2. Load Shedding Schemes

In this section, the different conventional load shedding schemes applied in power system operation and control are presented. The main operating principles, key attractions, drawbacks, and applications of each scheme are illustrated.

2.1 Breaker Interlock Load Shedding

This scheme is considered the simplest compared to other load shedding schemes. The main operating concept is that a source breaker is interlocked through hardwired or remote signals with different load breakers that have been previously selected to trip. In the case of any contingency, such as losing a grid supply or if a main generator breaker trips, a signal is sent to pre-selected load breakers, which causes them to trip automatically. As a result of these load breakers tripping, the system demand is reduced and the system stability is maintained. Figure 1 illustrates the operating scheme with breaker interlock load shedding.

The figure depicts four feeders that are being provided power by two synchronously running generators. In case of any supply fault, the main breaker of that generator will trip, sending the entire load onto the one connected generator. Hence, via interlocking, when the main breaker trips, it sends a tripping signal to pre-selected, interlocked load breakers, and thus the system load is reduced, as indicated by [13].

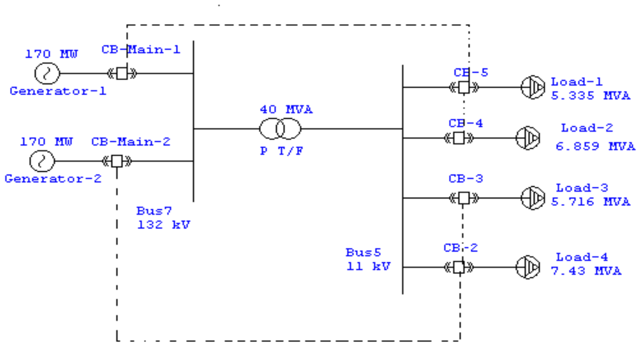


Fig. 1. System showing breaker interlock technique

Breaker interlock is a very efficient scheme, as it does not require any processing time. This is because the number and locations of loads to be shed have been previously set. Hence, this scheme is often applied when the speed of load shedding is crucial and immediate demand reduction is required. The key attractions of this scheme, as described in [13] and [16], are 1) simplicity and 2) instantaneous response. On the other hand, breaker interlock has inherent drawbacks, as indicated in [16]–[18]; these include: 1) system transience, which is not considered for the pre-selected breaker interlock list, and 2) unnecessary load shedding as a result.

2.2 Under-Frequency Load Shedding

The use of under-frequency relays to conduct load shedding is also a very effective technique. Principally, it considers fixed load reduction at fixed system frequency levels. As described in [17], the relay detects any rapid change or gradual deterioration in frequency and, in response, starts a staged operation of interlocked breakers. The relay is calibrated in several frequency-descending stages. When the relay picks up the first stage's preset frequency value, a tripping time is configured in the relay operation so as to avoid malfunctioning before it trips one or more load breakers. Other load breakers are scheduled to be tripped according to the subsequent load shedding stages of the preset descending frequency values selected by the relay. According to [16] and [19], at each stage, there is a predetermined tripping time. The sub-sequence is continued in stages until the system frequency is recovered.

To demonstrate the circuit configuration and the working principle of an under-frequency load shedding scheme, an example system is presented in Fig. 2. In such a configuration, the frequency relay might be calibrated in five subsequent stages according to different preset, descending frequency, and pick-up values. At each stage, a specific load breaker should trip and thereby reduce the power demand by some amount, which will help stabilize the system. The relay will trip the subsequent stages until the system becomes stable. Additionally, the number of stages might be reduced by allowing two or more load interlock breakers to trip simultaneously.

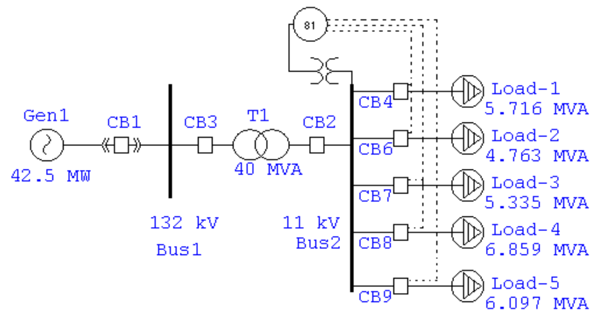


Fig. 2. System of an under-frequency load shedding scheme

Table 1 gives an example of preset stages when an under-frequency load shedding scheme is applied. As shown in the table, the feeders are disconnected in subsequent stages, with each disconnection occurring at a predefined frequency for the demand at each stage.

As indicated by [20] and [21], the under-frequency load shedding scheme is mostly used for overloaded power systems that usually experience instability due to a drop in the operating frequency. As [16]–[18] state, the key attractions of this scheme are that 1) it is simple and inexpensive to implement, 2) it is the most popular for systems that suffer from frequency dip instability problems, and 3) it restores frequency to stable conditions and avoids system collapse.

Table 1. Typical values for under-frequency load shedding stages.

Stage	Frequency (Hz)	Load (MVA)	Location
1	49	5.716	CB4
2	48.8	10.098	CB6 & CB7
3	48.6	6.097	CB 9
4	48.4	6.859	CB8

On the other hand, as [17] indicates, this scheme has technical drawbacks that include 1) independence of system dynamics, 2) slow response time, 3) a greater disconnected load amount than is actually required, and 4) it not being an optimal option.

2.3 PLC-Based Load Shedding

The technology of the programmable logic controller (PLC) has been applied extensively in both industrial and substation automation. As indicated in [17], since the early 1980s, PLCs have been applied in industry for load management. Generally, a PLC-based load shedding scheme is initiated by triggers such as deviations in the system's frequency. The scheme is programmed to trip load-specific, preset load circuit breakers according to system conditions of loading, available generation, and other triggering logics, such as frequency deviations. Several load shedding triggers can be adapted to initiate the scheme, such as frequency deterioration, over-current, and over-voltage, among others. The sequence of load shedding stages is continued until the system stability is restored to normal conditions. The PLC-based load shedding scheme can support load management as an additional function. The architecture of this scheme is depicted in Fig. 3.

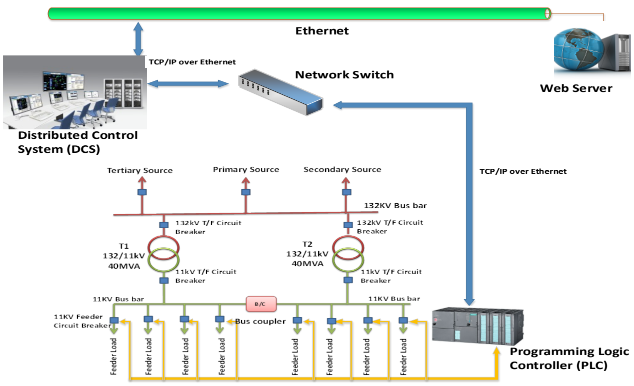


Fig. 3. Architecture of a PLC-based load shedding scheme

The PLC-based load shedding scheme is mostly applied when a quick response is required and when conditions changing in the power system must be considered. According to [16]–[18], the key attractions of this scheme are 1) faster response and greater precision compared to under-frequency load shredding and 2) its capability to handle changing power system conditions. On the other hand, as discussed by [13] and [17], this scheme also has technical drawbacks, including 1) increased cost and added complexity; 2) a non-dynamic nature; 3) the possible result of excessive load shedding; 4) limited system monitoring, as the condition for system-wide area monitoring is missing; and 5) being a sub-optimal option for a load shedding scheme.

2.4 AI-Based Load Shedding Scheme

To overcome the inherent drawbacks of the previously described conventional load shedding schemes, artificial intelligence (AI) has been proposed as a solution. Different AI methods have been considered; these include, for example, artificial neural networks (ANNs), fuzzy logic control (FLC), the adaptive neuro-fuzzy inference system (ANFS), particle swarm optimization (PSO), and genetic algorithms (GAs). This scheme is based on a comprehensive understanding of the power system's dynamics and its constraints, in addition to a knowledge base of system disturbances. According to [17], the purpose of AI-based load shedding is to improve response time, predict frequency decay, and find the optimum load to be shed. In this scheme, the problem is transformed into a non-linear optimization problem. In such a problem, an objective function is optimized with technical constraints. Figure 4 demonstrates the architecture of an AI-based load shedding scheme.

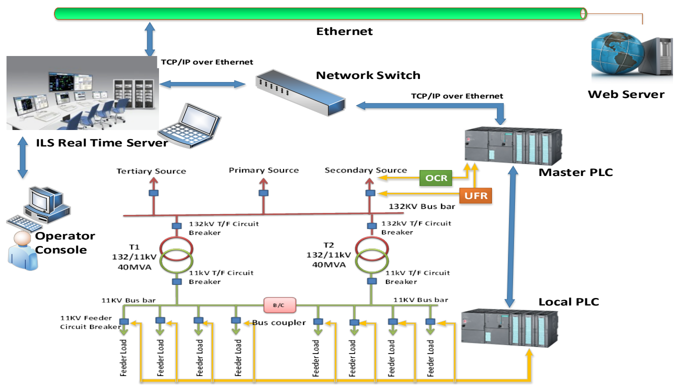


Fig. 4. Architecture of an AI-based load shedding scheme

The general block diagram for an AI-based load shedding scheme is presented in Fig. 5. The intelligent system is pre-trained based on offline system studies and simulations. Accordingly, the load shedding tables are updated based on periodic system knowledge. This results in optimum load shed in case of a disturbance. To improve the response time, as noted in [17], shedding tables are downloaded and assigned to the local distributed controls that are close to the sheddable loads.

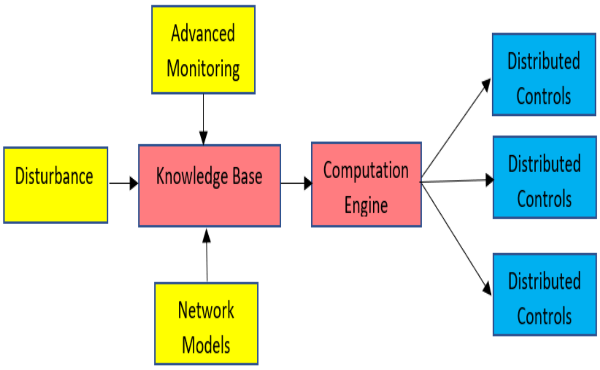


Fig. 5. General block diagram for AI-based load shedding

When applying a conventional load shedding scheme, the trigger signal is initiated according to the system frequency or its derivative. This approach is efficient for industrial applications in which the generating capacity varies considerably, there is a flexible distribution network, the frequency decay rate is high, and the number of loads is small and limited. Hence, the application of an AI-based shedding scheme is much preferred for such cases. As described in [16]–[18], the key attractions of this scheme are 1) a fast response time, 2) adaptation to the system dynamics, and 3) optimal solution results with a minimal load shed. On the other hand, as noted in [13] and [16], this scheme has technical drawbacks, which include 1) a requirement for a large quantity of equipment, sensors, and high-tech servers, in addition to advanced software capabilities; 2) the limitation that it might not be applicable to old grids; 3) the requirement of too much system data; and 4) expense and the need for specialist engineers in AI.

3. PESCO Power System and Existing Load Shedding Scheme

This section describes and discusses the power system of PESCO and the load shedding scheme that it currently applied.

3.1 System Description

PESCO is a power distribution company located in Peshawar province in Pakistan. PESCO provides power services to over 2.6 million customers within Khyber Pukhtunkhwa, Pakistan. The company maintains an electricity distribution system through a grid with sub-transmission lines at different medium voltage levels: 132 kV, 66 kV, and 33 kV. It also has sub-stations and 11 kV and 440 V low-voltage lines with distribution transformers that deliver electricity to customers. As shown in Fig. 6, PESCO operates over a geographical area of about 1,204,621 hectares. This is divided into eight regions, or circles, as follows: Bannu, Hezra-1, Hezra-2, Khyber, Mardan, Peshawar, Swabi, and Swat.

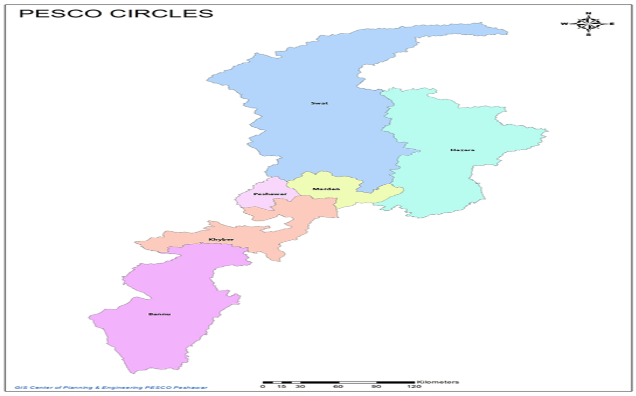


Fig. 6. PESCO jurisdiction circles

3.2 The Existing Load Shedding System at PESCO

The main reasons for severe energy shortages, as noted in [1, 25], include inadequate addition in capacity; limited explorations; ineffective exploitation of coal, hydroelectric, and renewable potentials; and inefficient use of energy resources. All these factors result in load shedding of electricity, which increases daily as the shortfall increases. In July 2016, the supply deficit peaked at just over 7,200 MW, as mentioned in [3]. To avoid this continuous imbalance between supply and demand, load shedding has been carried out, mainly to maintain system stability and to avoid complete blackouts. Fig. 7 illustrates the imbalance between supply and demand in GW from 2011–2016.

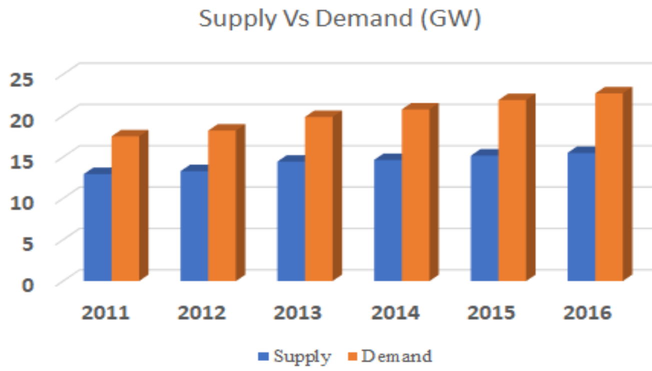


Fig. 7. Supply vs. demand in GW (2011–2016)

In PESCO, the current applied load shedding scheme is essentially based on preset tables, which causes excessive shedding and customer loss despite any economic considerations that might affect the company revenues. PESCO has also initiated peak/off-peak schedule timings for industries, which is resulting in better diversity of factors for distribution of electricity. Over the last few years, PESCO has upgraded its communication infrastructure by installing AMR meters to all feeders, incoming panels, input/output transmission lines, breakers, source breakers, and important consumers. These AMR meters transmit the required data to a central location, called the power distribution center (PDC), for monitoring the equipment loads and their behavior. The load shedding, however, is conducted manually by the officials in the grid station by turning the feeder breakers on and off. Fig. 8 depicts the architecture of the existing system at PESCO.

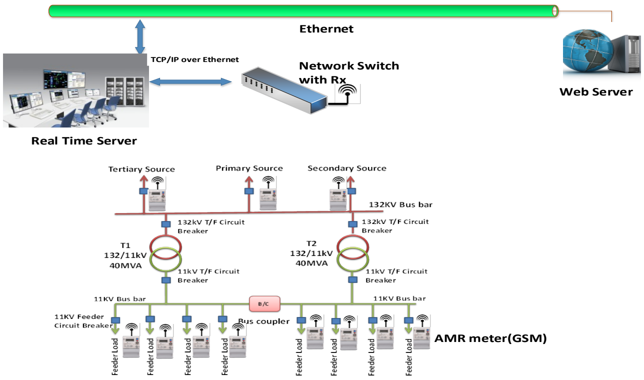


Fig. 8. Architecture of existing system installed at PESCO

PDCs at PESCO were constructed with state-of-the-art real-time servers, monitors, and switches for receiving data from the AMR meters installed in the field. Trained PDC professionals are available around the clock to monitor the load flow and pass on instructions over the telephone to switch any breaker on or off as per load shedding requirements. The installed AMR meters use global system for mobile communications (GSM) technology to send required data through a short message service (SMS) to the PDC receiver switches, which then compute and display them on the large screens at the PDC. The system can also be accessed through the Internet by authorized personnel to monitor the system remotely. The data traffic is only one way, as the data acquisition is being done via GSM/SMS, but no instructions in response are passed on for switching.

Presently, for every feeder installed in PESCO, the data SMS is sent every 15 minutes from the feeder to the monitoring center (PDC). The SMS is received by the PDC receiver and decoded to display it on the monitoring screen and pass it on to the server. Different mobile networks are utilized depending on the service area coverage of each network. Table 2 shows the content of data sent by the AMR meters for each type of equipment to the PDC. Table 3 shows the number of SMS transmissions generated by AMR meters and received by the PDC per month. The payment for these SMS transmissions is made by PESCO to the mobile operator companies.

The PDC receives the percentages of revenue return and losses for every feeder in every grid station from the PESCO Computer Center (PCC). The PCC carries out these calculations by comparing the kWh units consumed or billed to the consumers on the feeder and the kWh units sent out on the feeder by the grid station. Based on this calculation, load shedding schedules are formulated by the PDC. The greater the percentage of revenue return, the fewer the load shedding hours on the feeder. The same schedule is passed on to the grid station staff to carry out load shedding. The PDC may revise the schedule from time to time to fit the needs of the system and convey the said changes to the GSS staff for implementation. The officers of the PESCO utility company, having been provided the company password, can visit the PESCO website to easily access the data from each piece of equipment. Similarly, the data for AMR meters installed in consumer premises can easily be accessed by any consumer via the Internet, as pointed out by [22,23]. The load shedding schedule is issued to GSS officials on a monthly basis to conduct the load shedding of feeders as per the times and dates mentioned in the schedule. The system is totally manual, and no automated function is involved in the load shedding process. The official on duty follows the schedule to manually turn the feeders on or off at different times of day. Under-frequency relays are installed in 11 kV control rooms of GSS for tripping different interlocked feeders at different frequency stages of the relays. Similarly, under-frequency relays are also installed on 132 kV transmission lines to trip different lines at different frequency stages.

Table 2. Contents of SMS transmissions from different equipment

Equipment	Contents of SMS Transmission
11kV O/G Feeders	Feeder code, Time, Date, I, V, kWh, kVARh, PF
11kV Incomings	Incoming Code, Time, Date, I, V, kWh, kVARh, PF
132kV T/Lines	Line Code, Time, Date, I, V, kWh, kVARh, PF

Table 3. Calculation of SMS transmissions in the existing system

SMS Transmission Calculations in the Existing System	
No. of GSS	90
No. of outgoing feeders	867
No. of incoming breakers	114
No. of line breakers	252
Total equipment	1,233
No. of SMS transmissions/day	177,552
No. of SMS transmissions/ month	5,326,560

4. Proposed Experimental Load Shedding Scheme

To minimize the cost of infrastructure and to maximize its output in the proposed load shedding scheme, the following changes have been proposed to the existing PESCO system. With the introduction of AMR meters by USAID EPP, one-way communication became possible, but to provide two-way communication, PLCs should be added with receivers. The added PLCs are programmable, and instructions may be passed on for switching in emergencies or disturbances. The details are given in the block diagram shown in Fig. 9.

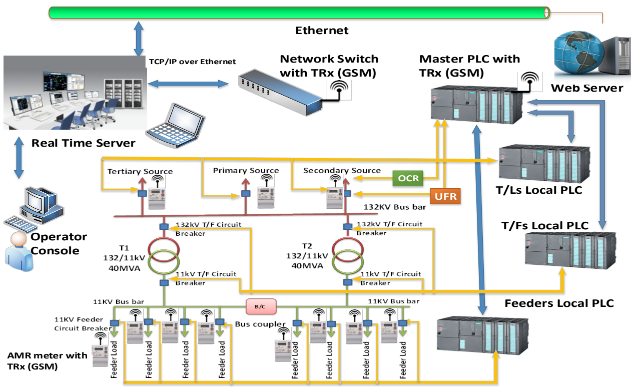
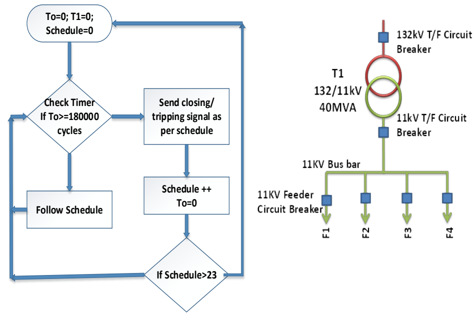


Fig. 9. Proposed experimental load shedding scheme

The three local PLCs are connected to the master PLC through cables, whereas the master PLC is connected to the control center through a wireless communication link. The local PLCs could also be interconnected via WiFi (the latest PLCs, such as the Siemens S7 1215C, come with WiFi compatibility). The local PLCs are connected to the tripping and closing coils of the feeder, transformer, and transmission line breakers. The AMR meters are only used for monitoring, which can be done from the PDC or remotely from the Internet. Different changes and components have been added to the proposed system, such as PLC, a real-time Server, an operator console, automatic meter reading units, and a data concentrator unit.

Certain protocols were defined for the system to ensure smooth running and to perform the desired operations. In the proposed scheme, PLCs will be provided defined protocols to follow in normal conditions or in case of faults. Fig. 10 illustrates the flow chart of the proposed load shedding scheme to be implemented. The PLC will control the opening and closing of each feeder breaker as per the schedule provided by the PDC. Each breaker contains a tripping and a closing coil, which when energized trips or closes the breaker, respectively. The PLC will generate a tripping or closing pulse at designated times. Fig. 11 depicts the feeder loading as per the proposed load shedding schedule.



Feeder	Time of Day																						
	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
F1	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓
F2	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓
F3	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓
F4	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓

Fig. 10. Flow chart for normal load shedding along with the load shedding schedule

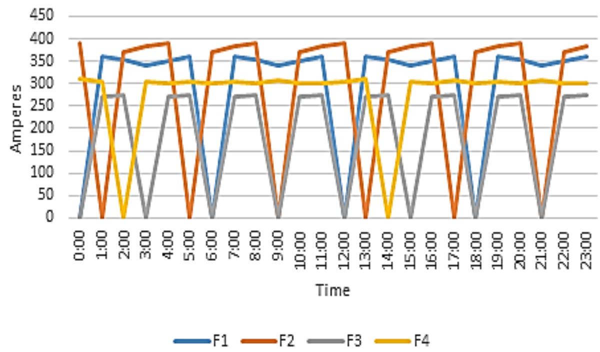
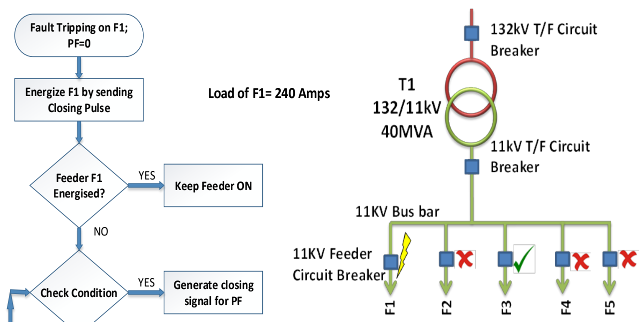


Fig. 11. Loading of feeders as per the load shedding schedule

In Fig. 12, the priority of the feeders has already been programmed into the PLC as per the revenue return percentage of each feeder; however, the suitable replacement also needed to have a lower load than the fault feeder. Hence, in this case, Feeder F2 is a suitable choice.



Feeder	Load	Revenue Return	Priority
F5	290 A	96%	1
F2	230 A	92%	2
F4	320 A	65%	3

Fig. 12. Flow chart for operation of feeder during fault and its conditions

Figure 13 shows a flowchart of the PLC's method of frequency control. The PLC will be provided the under-frequency relay output so that it can trip the group of pre-selected feeders for pre-defined low frequency readings. Feeders F1 and F2 are electrically interlocked to trip when the frequency drops to 49.8 Hz (Stage 1). Similarly, Feeders F3 and F4 trip when the frequency drops to 49.6 Hz (Stage 2) and 49.4 Hz (Stage 3), respectively. For programming a set of feeders to trip for under-frequency relays, the same programming as in 5.2.1.a is to be used, except a "Tripping via Frequency" switch will be added parallel to the "Tripping via Relay" switch and will be connected to the under-frequency relay for tripping. To electrically interlink the feeders to trip on the same frequency, the "Tripping via Frequency" switch will be used for interlinked breakers. Figure 13 shows interlinked breakers Feeder 1 and Feeder 2, which will trip at frequency 49.8 Hz.

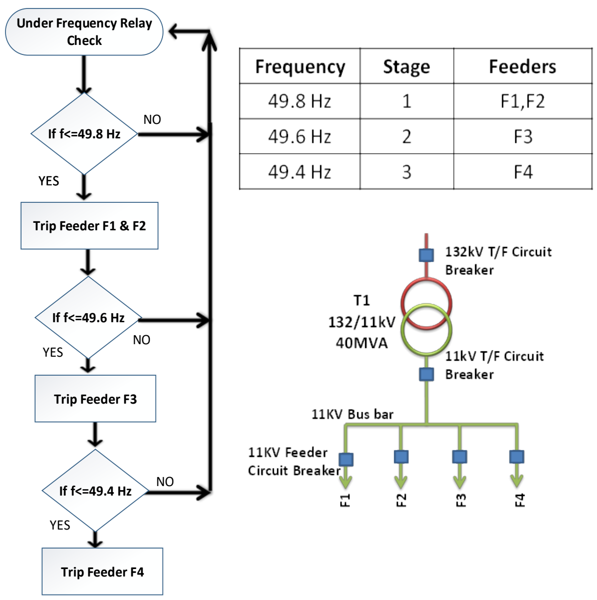


Fig. 13. Flow chart for operation during under-frequency instability

5. Simulation Results and Discussion

To investigate the proposed load shedding scheme, different case studies were conducted. In this section, the analysis and results of these case studies are presented.

5.1 Case Study 1: Transmission Line Switching

For this case study, the 132 kV GSS Jamrud has been selected, which is a critical grid switching sub-stations. The primary source of the 132 kV GSS Jamrud is the Warsak Powerhouse, and the secondary source is the 500 kV GSS Sheikh Mohammadi via the 132 kV GSS Peshawar University. In addition, Jamrud GSS also acts as a source for the 132 kV GSS Hayatabad and the 132 kV GSS Landi Kotal. The peak load on the Warsak–Jamrud line is 470 A in July, whereas the minimum load is 370 A in February. During the case study, data were collected for the breakdowns resulting from the fault in 2015 in the primary transmission line and how much time it took to restore the power via the secondary transmission line using the present infrastructure. From Table 4, it is evident that breakdowns occurred eleven times, and the grid sub-station outage lasted 504 minutes (8.4 hours) until power was restored. Considering the equation in terms of profit and loss, at an average load of 420 A on the 132 kV side, PESCO failed to supply 442,411 kWh to consumers during this down time. Deducting the generation price and taxation, PESCO lost Rs 4.1 million (not including the extra rates for peak times, which may have increased the loss). This loss is calculated for only the 132 kV GSS Jamrud sub-station, which has 34 feeders and 4 power transformers. If all the PESCO grid stations and their down times are collected for a year, the loss goes much beyond this calculation

Table 4. Downtime for the Warsak–Jamrud transmission line at GSS Jamrud in 2015.

Sno	Controlling Breakers	Fault Indication	Date	Time of fault	Supply restoration Time via Sec. source	Down Time (min)
1	L4-JMR1	B-phase Zone-1	5-Jan-15	2:41	3:32	51
2	L4-JMR1	R-phase Zone-1	27-Feb-15	18:22	19:15	53
3	L4-JMR1	R-phase Zone-1	16-Apr-15	11:13	11:47	39
4	L4-JMR1	B-phase Zone-2	19-Apr-15	21:32	22:41	69
5	L4-JMR1	3-phase Zone-1	2-Jun-15	20:55	21:37	42
6	L4-JMR1	B-phase Zone-3	21-Jun-15	19:14	20:02	48
7	L4-JMR1	Y-phase Zone-1	25-Jun-15	1:26	1:55	29
8	L4-JMR1	B-phase Zone-1	2-Jul-15	13:38	14:16	36
9	L4-JMR1	R-phase Zone-3	26-Aug-15	19:53	20:31	38
10	L4-JMR1	3-phase Zone-2	19-Nov-15	23:42	0:40	58
11	L4-JMR1	B-phase Zone-1	1-Dec-15	19:01	19:42	41

The proposed load shedding scheme has been analyzed for the breakdown on August 26, 2015. In this event, the supply was restored to the 132 kV GSS Jamrud within 38 minutes. Figure 13 shows the difference in downtime between the existing load shedding scheme and the proposed load shedding scheme. The graph clearly shows a large improvement in the response time of the proposed load shedding scheme compared to the current scheme.

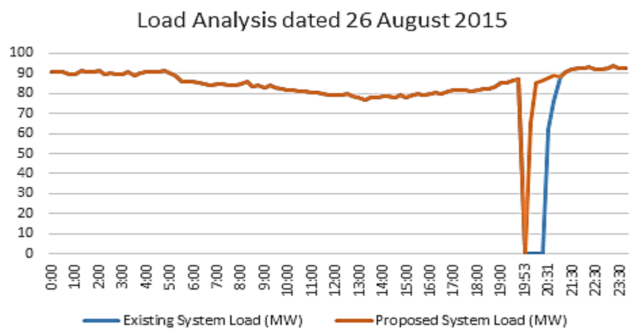


Fig. 14. Downtime for existing and proposed systems on August 26, 2015

5.2. Case Study 2: Transformer switching for GSS Peshawar Industrial

For this case study, the 132 kV GSS Peshawar Industrial was selected, which is also a critical grid sub-station that supplies power to a small industrial estate, inner-city residencies, and ring road outskirts. The GSS is fed primarily from the 500 kV GSS Sheikh Mohammadi and secondarily via the GSS Peshawar University. The GSS has three 132/11 kV power transformers rated at 37.5/40 MVA. The transformers T1 and T2 are interlinked through a bus coupler. The maximum load on power transformer T1 during July 2016, was 1,860 A, whereas the maximum load on power transformer T2 was 1,820 amps. In case of any fault in the differential zone of a power transformer (power transformer, 132 kV CT, 11 kV CT; 132 kV lightening arrester; 11 kV lightening arrester; power cable, 132 kV circuit breaker, and an 11 kV incoming circuit breaker), the supply to the affected feeders is provided from the other power transformer by closing the bus coupler and managing the load. If the load of the non-affected feeder is also high (usually in summer season), the bus coupler should not be operated. In this case study, we took the example of power transformers T1 and T2 and investigated the bus coupler operation on August 1, 2016, when the breaker of the power transformer tripped due to low SF6 pressure. Figure 15 shows the maximum loads of the feeders on August 1st, along with the percentage of revenue return and the extent of load shedding carried out on each feeder. Figure 16 displays the bus loading graph of each bus in MW. The recovery and losses are shown in Fig. 17.

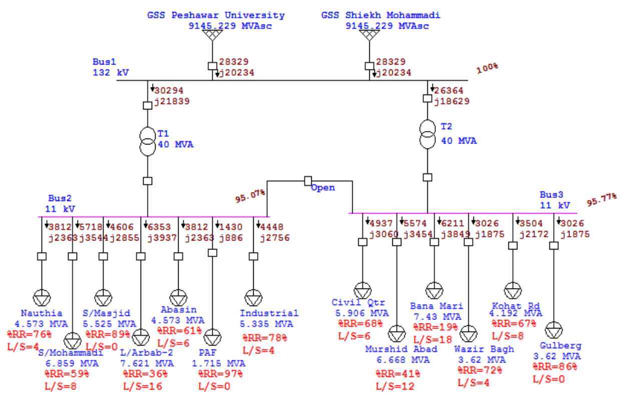


Fig. 15. The full load capacity of power transformers T1 & T2 at the 132kV GSS Peshawar Industrial on August 1, 2016.

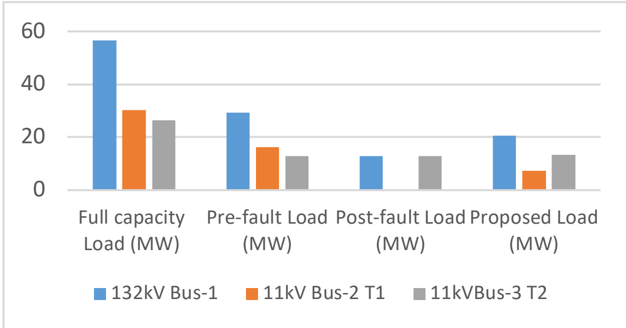


Fig. 16. Load analysis of buses at different stages

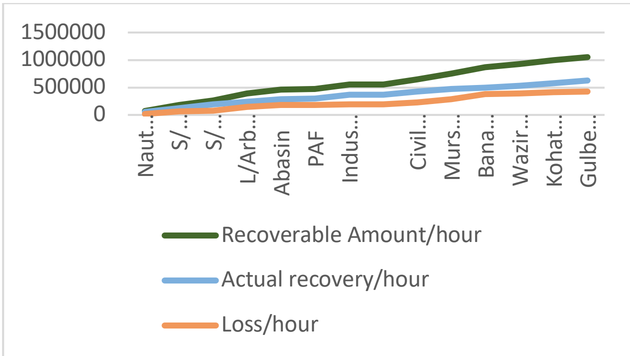


Fig. 17. Graphical representation of operation, recovery, and losses

5.3 Case Study 3: Feeders for GSS Peshawar University

In this case study, the 132 kV GSS Peshawar University is selected as an important GSS in terms of educational institutes, hospitals, and army residential areas. The GSS has three 132/11 kV power transformers rated at 37.5/40 MVA and delivering power through 27 feeders. The priority for each feeder is defined according to the revenue return percentage (%RR) of the feeder. The higher priority in return means fewer load-shedding hours. In the GSS, feeders' %RR values range from 17% to 96%;

hence, the load-shedding hours range from load shedding exemption to 18 hours. Figure 18 and Table 5 display the results collected for revenue return percentage and load shedding at power transformer T1.

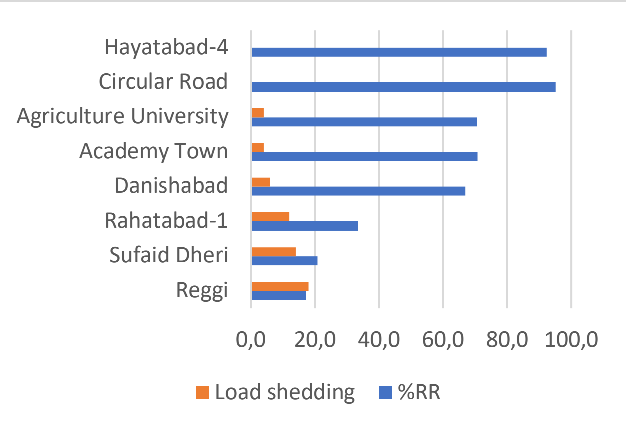


Fig. 18. Feeder %RR and load-shedding hours for T1 at GSS Peshawar University

Table 5: Feeder revenue return and load-shedding hours for T1 at GSS Peshawar University

Feeders of T-1	%RR	Load shedding
Reggi	17.2	18
Sufaid Dheri	20.8	14
Rahatabad-1	33.4	12
Danishabad	66.9	6
Academy Town	70.8	4
Agriculture University	70.6	4
Circular Road	95.1	0
Hayatabad-4	92.3	0

6. Conclusion

The applciation of smart grids leads to many advantages in the operation, monitoring and control of power systems and is considered a very promising solutinon to manage and avoid power outages [26]. With the power shortfalls in the Pakistan electricity grid, load shedding is applied daily to maintain system stability and reliability. This has a severe effect on the economic development of the country; it also impacts the daily routine of its people. The current applied scheme for load shedding is inefficient and results in long power outages at a high economic cost. Additionally, it results in excessive load shedding. In this paper, a novel experimental load shedding strategy for solving the power grid's existing issues has been proposed. As a case study, the proposed strategy has been applied and tested on the Peshawar Electricity Supply Company (PESCO). The proposed method outperformed the existing load shedding scheme in terms by minimizing the load shedding time with a lower economic impact. The proposed system has a cost-effective design based on the existing grid infrastructure and requires a minimal number of system upgrades.

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