Energy Management in Smart Distribution Networks with Load Shifting Using Cyber-Physical Systems

Abdolreza Sadighmanesh[1]
[1] Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Ahar, Iran
Email: Ab.Sadighmanesh@iau.ac.ir (corresponding author)
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Abstract

Traditional electricity distribution networks face significant limitations when confronted with increased load during peak hours. Voltage fluctuations, power quality degradation, and even widespread blackouts are among the consequences of this load increase. Cyber-Physical Systems, alongside renewable energy generators and energy storage units, enable intelligent and optimal control of energy resources. In this paper, an intelligent control strategy for dynamic load shifting from peak hours to off-peak hours is presented. Utilizing Cyber-Physical Systems and data obtained from load flow analysis, optimization algorithms have been designed to reduce energy production and distribution costs through intelligent load management and the energy stored in batteries. Simulations performed on the IEEE 33-bus system demonstrate that this proposed method effectively leads to reduced network losses, decreased operational costs, and improved system stability.

Keywords: Load Shifting, Cyber-Physical Systems, Smart Distribution Networks, Energy Management.

1. Introduction

Today, electricity distribution networks are transforming into smart grids. However, the increasing penetration of distributed generation resources based on renewable energies, as well as the growing number of prosumers who are both producers and consumers of energy, has significantly increased the complexity of network management. To address these challenges, there is a need for intelligent and flexible control systems that can respond dynamically and in real-time to network changes. Numerous articles have utilized Cyber-Physical Systems for the control and improvement of distribution network conditions. Reference [1] studies a distribution network equipped with AMI (Advanced Metering Infrastructure) and SCADA (Supervisory Control and Data Acquisition) systems and examines the impacts of advanced control systems of a smart distribution network on voltage regulation, power quality improvement, and reduction of environmental pollutants. In [2], intelligent management of a distribution network is carried out to improve reliability and network protection. The impact of communication systems in transmitting network data based on the extent of the fault, outage hours, and fault location on reducing voltage fluctuations and faults is studied. In [3], an information management and collection system in the customer-side distribution automation system is modeled for low voltage and current control. Intelligent perception devices were integrated and optimized for sensing, monitoring, and measuring operations in the distribution station area to enhance the panoramic state awareness of the intelligent terminal. Article [4] utilizes electric vehicle batteries for energy storage in the distribution network. Throughout the day, power injection by electric vehicle batteries during peak load hours helps improve the network's voltage quality, and the network remains in suitable voltage conditions throughout the day. The objectives of shifting load from peak to off-peak hours and reducing battery costs are the goals of this paper. Article [5] uses electric vehicle batteries for energy storage at dedicated parking locations for these types of vehicles in the distribution network. Throughout the day, power injection by electric vehicle batteries serves as a suitable alternative during certain hours instead of photovoltaic systems that have experienced power supply disruptions, into the distribution network. Article [6] performs peak load shifting using wind turbines and energy storage units. The mentioned article not only achieves peak load shifting in the distribution network but also realizes coordinated control between different energy storage units. Load regulation is performed throughout the day while preventing overcharging or over-discharging of the batteries. Reference [7] utilizes energy storage units to reduce the energy cost of distribution networks. Reference [8] employs energy storage units with an economic method for peak-to-valley (low load points of the daily load curve) shifting. The balance between the economic costs of batteries and peak shifting is a focus of the mentioned article. Article [9] uses batteries and capacitor banks for energy storage in the distribution network. Throughout the day, power injection by batteries and capacitors during peak load hours, in addition to peak shaving, helps improve the network's voltage quality and prevents voltage drop on the buses during peak load hours. Article [10] implements battery energy storage systems in a real 500-bus Spanish medium-voltage network. It analyzes the network under sustainable load growth scenarios. Finally, the mentioned article performs distribution system planning for peak load modification on an annual schedule. Reference [11] presents a hybrid method using a genetic algorithm for locating renewable generators to reduce network power losses and improve bus voltage profiles.

In this paper, load flow analysis using a 24-hour load curve in the distribution network is used to investigate the key role of intelligent control in balancing energy production and consumption in distribution networks. The peak load values and peak hours of the network, the energy consumption cost of each bus and the entire network are determined using a three-tiered tariff. Online controls and adjustments are made to break the peak load and balance the load between peak and off-peak hours. These adjustments include the operational modes of charge and discharge for batteries installed in the network and the scheduling of controllable loads. The load of all network buses is sent hourly to the control center by cyber-physical systems, and the control center, by aggregating the total network consumption curve, makes changes to the consumption curve of the buses. In this paper, the three-tiered tariff of the Canadian province of Ontario has been used to calculate the 24-hour electricity cost of the buses. To demonstrate the effectiveness of the proposed method, simulations have been performed on the IEEE 33-bus system. The results presented in this paper indicate the advantages of the proposed method in improving the energy consumption curve of the distribution network and shifting the peak load to off-peak hours, reducing system losses, and decreasing the operational costs of distribution networks.

2. Problems of distribution network operation during peak load

Traditional distribution networks, primarily designed for one-way power flow from power plants to consumers, face significant challenges during peak load times. These problems include:

Increased Energy Losses: With increased load and consequently higher current flowing through distribution lines, energy losses in transmission and distribution lines increase due to resistive and reactive effects, leading to significant energy wastage.

Voltage Drop: During peak load, the voltage drop across buses and distribution lines becomes considerable due to increased load current, which can negatively impact the performance of consumer equipment.

Voltage Stability: Maintaining voltage stability in traditional distribution networks, especially during peak load due to sudden load changes and the presence of distributed generation resources, is very challenging.

Reduced Power Quality: Increased harmonics, voltage fluctuations, and frequency variations during peak load lead to a decrease in the quality of power delivered to consumers.

Difficulties in Load Management: Traditional networks lack the ability for dynamic and real-time load control and management, which leads to problems in balancing supply and demand.

Today, to address the aforementioned problems and achieve economic savings, traditional networks are being transformed into smart distribution networks. Smart grids, leveraging information and communication technologies, enable intelligent and efficient energy management. The benefits of using smart grids in peak load management include:

Reduced Energy Losses: By using power flow optimization algorithms and active network management, energy losses can be significantly reduced.

Improved Voltage Stability: Utilizing advanced control systems, coordinating distributed generation resources, and shifting a portion of the peak load to off-peak hours can improve network voltage stability.

Reduced Voltage Drop: Voltage drop in the network can be reduced by employing compensation equipment and intelligent load control.

Increased Power Quality: The quality of power delivered to consumers can be improved by using harmonic filters and power quality control equipment.

Active Load Management: With intelligent metering technologies and two-way communication, the load can be managed dynamically and in real-time, establishing a balance between supply and demand.

3. Formulation and Modeling of the Studied System

The modeling and simulations in this paper have been performed on the IEEE 33-bus test system [13]. In this network, some buses have been equipped with batteries for storage and the capability of load control by the dispatching center.

One of the important results of load flow calculations is the amount of losses in the distribution lines. In distribution networks, the primary concern is the losses due to power flow through the resistance of the distribution lines. The power equations are expressed by Equations (1) and (2).

$$P_i = V_i \sum_{j=1}^{n} Y_{ij} V_j \cos(\delta_i - \delta_j - \gamma_{ij}) \qquad (1)$$

$$Q_i = V_i \sum_{j=1}^{n} Y_{ij} V_j \sin(\delta_i - \delta_j - \gamma_{ij}) \qquad (2)$$

In these equations, (P_i), (Q_i), (V_i), (Y_{ij}), (δ_i), and (γ_{ij}) represent the active power, reactive power, voltage of the (ith) bus, admittance between the (ith) and (jth) buses, voltage angle of the (ith) bus, and admittance angle between the (ith) and (jth) buses, respectively.

For the analysis of the peak shaving problem in this paper, load flow calculations have been performed in two modes, and the comparison of energy costs in the mode with assistance has been done using the following relations.

$$PL_{\mathrm{bus,i}} = \{PL_{\mathrm{i,t}}\}_{\mathrm{t=1,\ldots,24}} \qquad (3)$$

$$PL_{\mathrm{bus\ new,x}} = PL_{\mathrm{bus\ old,x}} - \mathrm{a} * P_{\mathrm{Bat}}; \qquad (4)$$

Discharge mod

$$PL_{\mathrm{bus\ new,x}} = PL_{\mathrm{bus\ old,x}} + \mathrm{a} * P_{\mathrm{Bat}}; \qquad (5)$$

charge mod

In the above relations, i is the bus number, t is the hour of the day, PLbus,i is the active power of the (i-th) bus, ($PL_{\mathrm{i,t}}$) is the active power of the i-th bus at time t, ($PL_{\mathrm{bus\ new,x}}$) is the power of bus x after charging or discharging by the battery, ($PL_{bus\ old,x}$) is the power of bus x before charging or discharging by the battery, a is the power factor of the battery, (P_{Bat}) is the battery power. The negative sign in (4) indicates that some of the active power of bus x is reduced and this power is supplied by the battery connected to the bus and the battery is being discharged. The positive sign in (5) indicates that the active power of bus x is increased by the amount of battery power and this power is drawn from the grid by the battery connected to the bus and the battery is being charged. The transfer of power of buses x during peak hours to off-peak hours is carried out by (4) and (5).

Electricity tariffs in different countries vary greatly. In this paper, the Ontario three-price electricity tariff is used. The price of electricity per kilowatt-hour of electricity is also defined as a power unit (PUE) and can be expressed by the following equation.

$$C_{grid}^{t} = C_{PUE}^{t} \times P_{grid}^{t} \times \Delta t \qquad (6)$$

In (6) where (P_{grid}^{t}) is the grid power. The superscript t in all variables represents the length of the hour t. The variable (C_{grid}^{t}) is the grid power price. (C_{PUE}^{t}) is the time-dependent tariff. Δt is a specific time period.

The energy consumption cost of the busbars and the distribution network is calculated by the following relations.

$$a_{low} = C_1 \qquad \text{A: } 0 < t \le t_1 \qquad (7)$$

$$a_{mid} = C_2 \qquad \text{B: } t_1 < t \le t_2 \qquad (8)$$

$$a_{full} = C_3 \qquad \text{C: } t_1 < t \le t_3 \qquad (9)$$

$$\mathrm{T} = \{\mathrm{A, B, C}\} \qquad (10)$$

In equations 7 to 9, coefficients C1, C2, and C3 are the cost coefficients of the three time periods: low load, medium load, and high load, respectively.

In (10), T is the total time of a day and night, which includes three time periods: low load, medium load, and full load.

$$\begin{cases} Cost_{\mathrm{A,i,t}} = \mathrm{PL_{bus,i,t}} \times C_1 \\ Cost_{\mathrm{B,i,t}} = \mathrm{PL_{bus,i,t}} \times C_2 \\ Cost_{\mathrm{C,i,t}} = \mathrm{PL_{bus,i,t}} \times C_3 \end{cases} \quad (11)$$

$$Cost_{\mathrm{T,i,t}} = \sum_{\mathrm{t}=0}^{t_1} Cost_{\mathrm{A,i,t}} + \sum_{\mathrm{t}=t_1}^{t_2} Cost_{B,\mathrm{t}} + \sum_{\mathrm{t}=t_2}^{t_3} Cost_{\mathrm{C,i,t}} \quad (12)$$

$$Cost_{\mathrm{T},T,\mathrm{t}} = \sum_{\mathrm{i}=2}^{\mathrm{Total_{bus}}} Cost_{\mathrm{T,i,t}} \quad (13)$$

$Cost_{\mathrm{A,i,t}}$ ،$Cost_{\mathrm{B,i,t}}$ و $Cost_{\mathrm{C,i,t}}$ are the energy consumption cost of the i-th bus in time interval A, B and C, respectively. $(Cost_{\mathrm{T,i,t}})$ is the total energy consumption cost of the i-th bus during the day. $(Cost_{\mathrm{T},T,\mathrm{t}})$ is the total energy consumption cost of the entire distribution network during the day. $(\mathrm{Total_{bus}})$ is the number of buses in the distribution network. The reason why i=2 in (13) is that the load buses start from number 2 and bus 1 is the reference bus.

4. Program execution algorithm

The load flow program execution algorithm is performed in two modes. In both modes, the information of the IEEE 33-bus distribution network is input to the computer. This information includes line impedances, bus load curves, and the price and hours of the three-tiered tariff. Also, in both modes, load flow is performed using the backward-forward sweep method, and the power flow through the lines and system losses are determined. Consequently, the power of bus one, which is the sum of the power of the buses and system losses, is calculated. This power is the power drawn from the sub-transmission network.

Mode (1): Load flow is performed using the 24-hour load curve, or in other words, the load flow operation is executed 24 times using the daily load curve of the distribution network. The peak load value and peak load hours of the network, which are the main results of this mode, are determined. Another result obtained in this mode is the energy consumption cost of each bus and the entire network using the three-tiered tariff.

Mode (2): Using the results of Mode (1), the dispatching center performs 24-hour scheduling with cyber-physical control to break the peak load and balance the load between peak and off-peak hours by making online adjustments and controls. These adjustments include the batteries installed in the network and the controllable loads. The load of all buses in the network is sent hourly to the control center by cyber-physical systems, and the control center, by summarizing the total network consumption curve, makes changes to the consumption curve of the buses. During off-peak hours of the network, the batteries are in charging mode, and during peak load hours, the batteries discharge and inject power into the network. As a result, during off-peak hours, the power drawn from the distribution network increases, and during peak load hours, the power drawn from the sub-transmission network decreases. Also, by controlling the startup times of controllable loads, the power consumed by these loads is shifted from peak load hours to off-peak load hours. Another result of peak load shaving and load shifting to off-peak hours is the reduction in the energy cost of the buses, as the price of electricity varies at different times. It is worth noting that a three-tiered tariff has been used to determine the electricity price for consumers.

5. Simulation Results

The 24-hour active power curves of some buses in modes (1) and (2) are shown in Figure 1. The blue lines represent the 24-hour power of the buses in mode (1), and the red lines represent the 24-hour power of the buses in mode (2). The average active power of the buses in mode (1) is shown with a dashed line for better visualization of load changes. Controllable batteries with cyber-physical control by the dispatching center are used on buses 4, 7, 8, 14, 24, 25, 29, 30, 31, 32 (10 buses). Additionally, the control of controllable loads on buses 3, 4, 5, 6, 7, 8, 9, 13, 15, 16, 20, 21, 22, 23, 26, 28, 28, 29, 30, 31, 32 (21 buses) is also performed by the dispatching center using the physical layers of PLC power line communication systems. The energy stored in the batteries is considered to be 10% of the power consumption of each bus during the peak hour (hour 18), and the power consumption of each controllable load is considered to be 20% of the bus power consumption during the peak hour.

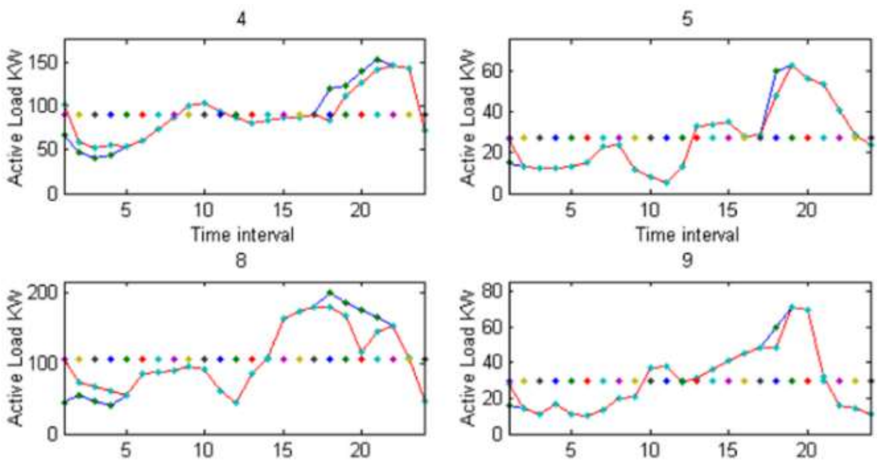

Fig. 1: 24-Hour Active Power Curve of Some Buses in Modes (1) and (2)

After the load flow analysis in both modes, the amount of active and reactive power drawn from the sub-transmission network (bus one) is shown in Figures 2 and 3.

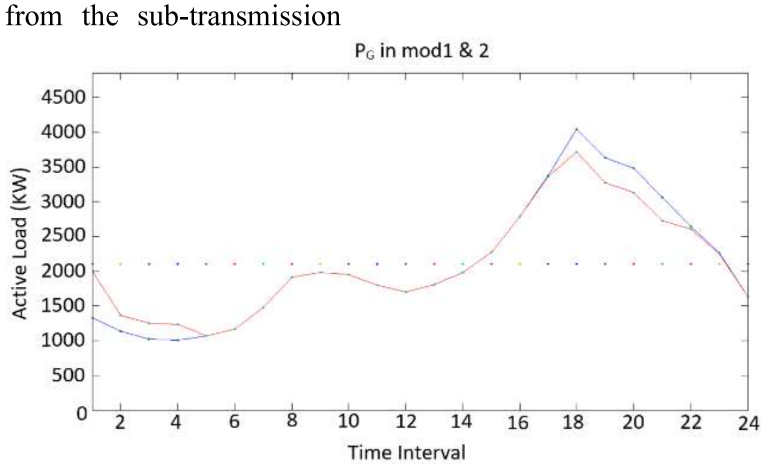

Fig. 2: Amount of Active Power Drawn from Bus One in Modes (1) and (2)

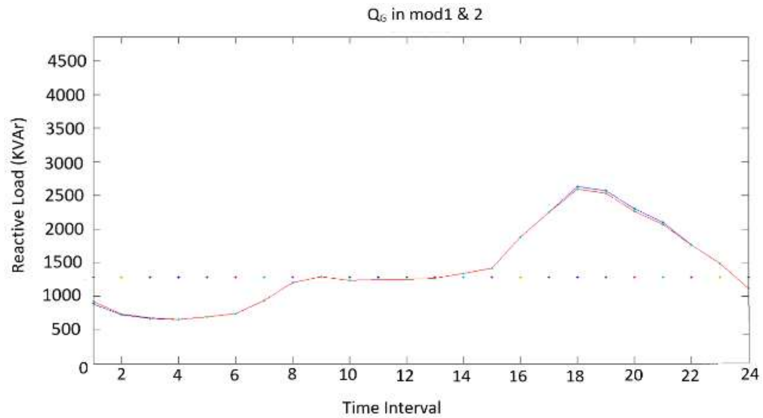

Fig. 3. Reactive power drawn from bus 1 in modes (1) and (2)

The system losses plus the active power of the system determine the power of bus 1. Although there are no changes in the reactive power of the load buses, the reactive power of the system also changes slightly due to changes in the active power of the buses, which can be seen in Figures 5-6 and 5-7. In general, due to the load transfer from peak to off-peak hours, the load curve is slightly adjusted and decreases during peak hours, and there is an increase in the load curve by the same amount during off-peak hours. The cost of electricity consumed by all 32 buses is shown in Table 1.

In Mode (1), the network is in normal operating conditions and no cyber-physical control is performed by the distribution network telecommunications system.

In Mode (2), the batteries and the controlled load system are controlled by the dispatching center to transfer peak load to off-peak hours, and the PLC system plays an effective role in reducing peak load and transferring power consumption to off-peak hours.

Table 1 Cost of electricity consumed by buses in 24 hours (cents)

Mod (2)	Mod (1)	Bus Nu.
28625.7	28625.7	2
17546.8	17714.2	3
32892.6	33389.4	4
10097.0	10151.0	5
9520.8	9632.4	6
25713.9	26733.9	7
37732.8	38752.8	8
10995.6	11049.6	9
16281.6	16281.6	10
13672.5	13672.5	11
9823.8	9823.8	12
11295.3	11406.9	13
36895.2	37284.0	14
17897.4	18009.0	15
16138.8	16192.8	16
18805.2	18805.2	17
20547.6	20547.6	18
18764.0	18764.0	19
17322.3	17489.7	20
21779.7	21947.1	21
11763.6	11931.0	22
12284.4	12365.4	23
46514.7	47875.5	24
51089.1	52449.9	25
15054.6	15108.6	26
14988.0	14988.0	27
16373.7	16485.3	28
22539.8	23151.8	29
37331.7	38351.7	30
28992.0	29757.0	31
51065.7	52136.6	32
13235.5	13235.5	33
713581.4	724109.6	otal buses co

In addition to reducing power consumption during peak hours and reducing the possibility of forced outages during these hours, the distribution network losses have been reduced due to load transfer to off-peak hours and reducing the flow during peak hours. The total active load of the network is 47666.9 kW, and by transferring 4734.5 kW of load, which is about 32.9% of the total network load, from peak hours to off-peak hours, the system losses during the day and night increase from 5.76 to 5.58. In other words, by transferring a little less than 10% of the load, about 0.2% of the losses are reduced. This is a significant amount in a distribution network where losses range from 5 to 6 percent. Also, the peak load at 6 p.m. has decreased from 4,047 kW to 3,717 kW. With the participation of 63% of the buses (20 out of 32 buses) in the controlled load plan and 31% of the buses with energy storage batteries, about 15.8% of the power has been reduced in the peak load. Network losses have decreased from 76.5% to 58.5%. Also, the cost of electricity for consumers has decreased from 724,109.6 cents to 713,581.4 cents during the day. That is, a 45.1% reduction in cost has been achieved.

6. Conclusion

Reducing the power flow through transmission lines during peak hours and shifting it to off-peak hours, in addition to direct technical benefits, leads to an overall improvement in network performance and reduced operational costs. Some of the most important advantages of this approach include:

By reducing the current flowing through the lines, resistive and reactive losses are significantly reduced, leading to substantial savings in energy consumption and reduced production costs.

Reducing the load during peak hours improves the voltage stability of the network and decreases the likelihood of phenomena such as voltage drop and voltage collapse.

With a more uniform load distribution throughout the day, the voltage profile of the buses improves, and the quality of power delivered to customers' increases.

Reducing the current flowing through equipment decreases the mechanical stress on the equipment and extends its lifespan.

By reducing the loading of equipment during peak hours, the rate of equipment aging decreases, and repair and maintenance costs are reduced. Decreasing energy production during peak hours, especially in thermal power plants, leads to a reduction in pollutant emissions and improved air quality. Furthermore, by reducing the loading of equipment, the reliability of the network increases, and the probability of outages decreases. Consequently, by implementing load management and load shifting strategies from peak to off-peak hours, the performance of the distribution network can be significantly improved, achieving the goals of sustainability and economic efficiency of the network, and reducing overall operational costs.

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