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Multiple DRPs to maximise the techno-economic benefits of the distribution network

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Abstract: This study addresses a demand response programme (DRP) model considering the price elasticity of demand to determine the peak scheduling for different categories of consumers with the possibility of load shifting. The main objective is to minimise daily energy loss and improvement in the node voltage profile of distribution system along with the economic benefits of different stakeholders. The proposed work helps in appropriate selection of DRP for different feeders/consumers. The investigations are performed on a benchmark 33-bus test distribution system and comprehensive analysis is illustrated through simulation results.

1 Introduction

In the context of smart distribution networks (DNs), distributed energy resources, controllable load and communication network plays an important role for technical as well as economic growth. The effectiveness of demand response programmes (DRPs) depends on the consumption pattern of consumers. The consumers of different categories are dedicated to specified feeders in the planning stage of the distribution system. More realistic modelling of DRPs is devised by considering the various load patterns of consumers for the same DN.

In 2018, the Indian ministry of power reported that the overall electricity generation is now increased to 330–1.3 GW, which was in the year 1947. According to the electricity act 2003, electricity to all is the primary focus but 19% of domestic electrification is still pending. However, the overall demand for system can increase even after installing 100% supply to all sectors [1]. Current scenario shows power curtailment of 8.3 times/month, which represents the deficit power in terms of peak and total generation availability [1]. Furthermore, high-power delivery loss is another challenge faced by the Indian power system which is reported ∼23% in 2018. Consequently, the finance commission of India reported that the cost of power purchase is increased from ₹680 billion to ₹1160 billion approximately which reflected on all the stakeholders [1]. It is observed that the responsive load has the ability to manage the peak demand and many different services for the DNs [2–4].

In [2], 15% peak demand reduction is estimated with the implementation of DR in the USA. Many of earlier studies focused on the potential of residential consumers and home energy management using DR to increase techno-economic benefit [5–10]. The coordinated response of customers was achieved with price-based home load management resulting in minimised peak rebounds and consumption cost [5]. It is observed that scheduling of home appliances with DR has a positive impact on Finnish residential DN and customer participation with DR results in technical benefits such as network losses and voltage profile [6]. In [7], automatic and optimal controls are suggested to minimise the waiting time and power consumption cost of residential customers in the presence of real-time pricing (RTP) tariff.

Furthermore, recent literature reported price and incentive-based DR coordination with distributed generation (DG) to alleviate intermittency of renewables and to improve the reliability of the power system [11]. The effectiveness of DR for the market participants such as independent power producer including risk constraints was observed along with imbalance reduction [12]. In [13, 14], strategy for economic benefits such as electricity cost minimisation with price-based DR and availability of DGs are explored. It has been observed that role of DR aggregator is not only limited to above-mentioned issues but now applications of DR are gradually shifting toward the electric vehicles (EVs) which may found to be the most important responsive loads in imminent future [15]. The uncoordinated charging of EVs may increase the peak demand of the system. Besides, costly peak generation is brought up to serve the peak load which consequently increases system cost and complexity [16]. The overloading of distribution feeders due to the increased EV fleet may reduce by the implementation of RTP tariffs [17]. Enormous benefits of DR implementation are reported in the existing literature with the inclusion of several responsive loads, issues, the effect of load curves and imbalances by dynamic pricing. It can be concluded from the aforementioned literature review that implementation of different uncoordinated and coordinated consumers' responses with DR affects the performance of the DN. Therefore, robust dynamic tariff structure plays a significant role in providing substantial benefits to all stakeholders of smart grid such as consumers, DN operator, generation company and aggregator. This paper highlights a dynamic tariff structure which improves the operation of demand side management and DR. The participation of consumers with different dynamic tariffs ensures that overall consumption cost of electricity will not exceed the initial bill amount. The residential, commercial and industrial consumers for the same distribution system with differently specified feeders having different price and incentive-based DR are implemented to analyse its impact on technical and economic parameters of the DN.

This paper is organised as follows. Different types of consumers and their load factor are summarised in Section 2. Problem formulation with elasticity, incentives, penalties, modified demand, voltage and power loss calculations are explained in Section 3. System data and discussion on results obtained are given in Section 4. Section 5 gives the final conclusions and outcomes of this paper.

2 Consumers load profiles

To evaluate the consumer participation effects on different DRPs, it is necessary for DR aggregator to know about the consumption behaviours with respect to electricity price. However, power consumption is unpredictable for the distribution company, as it depends on consumer behaviour. Even weekdays, weekends, summer and winter load profiles of a different class of consumers are also not the same, and therefore in the planning stage of distribution company dedicated feeders are provided for dissimilar groups of consumers. In this paper, a different class of load profiles such as residential, industrial and commercial is considered with

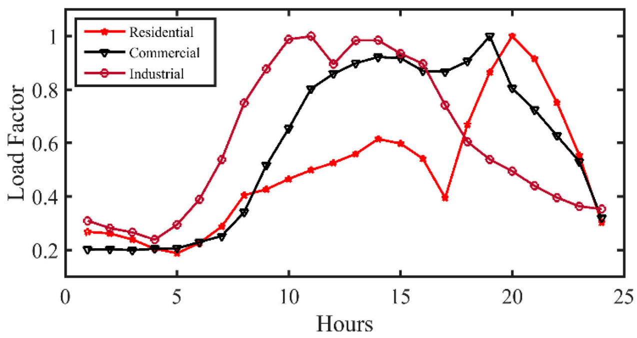

Fig. 1 *Load profile of customers*

the assigned dedicated feeders. Therefore, the effectiveness of DR with flexible electricity price elasticity of DN considering the diversified nature of feeders is analysed. For each class of consumers, the off-peak and peak period's consumption is considered to be different. Fig. 1 shows the load factors for different load profiles of 24 h of different types of consumers.

3 Proposed methodology

In this paper, multiple DR programmes for the different consumption patterns of the consumers which are dedicated to specified feeders are used. For the economic benefits of particular consumers, it is necessary to choose the appropriate DR because there are many DRPs floating by the power companies for increasing consumer participations. This paper is helpful in selecting the best suitable DRP for different consumers and also analysing the effect of particular DRPs by the DN perspectives. Furthermore, a compromising combination of DRP is suggested for the voltage profile improvement and energy loss minimisation of the DN. The electricity prices used for DRPs are also considering the negative pricing for the limited valley period to show the significant impact on the consumption patterns. This is also the need of the present scenario, where the penetration of renewables is high as it is growing enormously. Mathematical formulation of various programmes considering the effect of demand sensitivity (DS) is described in this section. The load profile with a time step of 1 h is considered.

3.1 Demand sensitivity

DS or elasticity is defined as the measure of modified demand with the effect of a change in the price of electricity [18, 19]. DS is the most powerful and effective way of modelling the behaviour of the consumer for DRP. Generally, the elasticity is expressed as

$$\varepsilon = \frac{c(i)}{d(i)} \frac{\Delta d(i)}{\Delta c(i)} \tag{1}$$

where ε and $c(i)$ are elasticity and electricity price of the ith time period. Self- and cross-elasticity are the two main coefficients of elasticity and are represented as

$$\varepsilon^{t} = \begin{cases} \varepsilon_{\text{self}} < 0 & \text{if } i = j \\ \varepsilon_{\text{cross}} > 0 & \text{if } i \neq j \end{cases} \tag{2}$$

where ε^{t}, $\varepsilon_{\text{self}}$ and $\varepsilon_{\text{cross}}$ are the elasticity, self-elasticity which are not able to move from one period of time to another period and cross-elasticity having the flexibility of shifting load, respectively.

3.2 Modified demand

Overall demand after and before applying the DR should be kept constant as it minimises the load curtailment and motivates the consumers for shifting the consumption pattern from peak to valley periods or off-peak periods. This increases the reliability of electricity in terms of load curtailment. Customer consumption for the time-based rate programmes is

$$D_{\text{m}}(i) = \psi_{\text{T}} \xi_{\text{d}} D_{\text{oi}}^{\text{T}}(i) \left\{ 1 + \varepsilon_{\text{self}}\, \gamma(i) + \sum_{\substack{i=1 \\ j \neq i}}^{24} \varepsilon_{\text{cross}}\, \gamma(i) \right\} \tag{3}$$

$$\gamma(i) = \left[\frac{c(i) - c_{\text{o}}(i)}{c_{\text{o}}(i)} \right] \tag{4}$$

where $D_{\text{m}}(i)$, ψ_{T}, ξ_{d} and $D_{\text{oi}}^{\text{T}}(i)$ are the modified demand after applying the DRPs, customer participation factor, maximum deferrable load and initial demand consumption of 24 h, respectively. Modified demand for the incentive-based DR programmes is related as

$$D_{\text{m}}(i) = \psi_{\text{T}} \xi_{\text{d}} D_{\text{oi}}^{\text{T}}(i) \left\{ 1 + \varepsilon_{\text{self}}\, \chi(i) + \sum_{\substack{i=1 \\ j \neq 1}}^{24} \varepsilon_{\text{cross}}\, \chi(i) \right\} \tag{5}$$

$$\chi(i) = \frac{[c(i) - c_{\text{o}}(\text{i}) + I(\text{i}) + P(\text{i})]}{c_{\text{o}}(i)} \tag{6}$$

where $I(i)$ and $P(i)$ are the incentives and penalty of the ith time periods.

3.3 Incentive and penalty

Incentives and penalty are the parts of mandatory type DR in which if the customer participated do not shift the consumption when directed are subjected to penalty; otherwise, incentive is added into the customer account. $\tau(i)$ is the incentive paid in Indian rupees (₹) to the consumer for the ith hour per kWh load reduction

$$I = \tau(i)[D_{\text{m}}(i) - D_{\text{o}}(i)] \tag{7}$$

$$P = \kappa(i)[\lambda(i) - (D_{\text{o}}(i) - D_{\text{m}}(i))] \tag{8}$$

Equations (7) and (8) are representing the overall incentive and penalty faced by the consumers, where $\kappa(i)$ is the penalty and $\lambda(i)$ is the contracted load of the same period.

3.4 Power loss

DR has the ability to shift the load pattern which results in changing the voltage and power loss of the feeders of the DN. Modified demand of nodes of particular feeder affects the voltage and power loss of the DN which can be measured by using the backward/forward sweep load flow analysis. Traditionally, maximum power loss occurs in the distribution systems during the power delivery which certainly affects the revenue of utility company. DRPs have the capability to reduce the power loss of the distribution company if appropriate programmes are selected. The feeder power loss is calculated as

$$P_{\text{L}} = \sum_{i=1}^{N_{\text{b}}} \sum_{j=1}^{N_{\text{b}}} \alpha_{ij}\left(P_i P_j + Q_i Q_j\right) + \beta_{ij}\left(Q_i P_j - P_i Q_j\right) \tag{9}$$

$$\alpha_{ij} = r_{ij} \cos\left(\delta_i - \delta_j\right) / V_i V_j \tag{10}$$

$$\beta_{ij} = r_{ij} \sin\left(\delta_i - \delta_j\right) / V_i V_j \tag{11}$$

Here, N_{b}, V_i, δ_i, P_i and Q_i are denoting a number of buses, angle, voltage magnitude, real power and reactive power injection at the ith node, respectively.

4 Results and discussion

The proposed model of different DRPs is applied to a benchmark test distribution system of 33 bus [20]. The system information of 33-bus test system is shown in Table 1. Electricity tariff of the base case, incentives, penalty per kWh and different DRPs are shown in Table 2. Generally, two types of DR programmes are used in the power market. The time-based programmes such as time of use (TOU), RTP and critical peak pricing (CPP) which are generally suitable for the residential consumers as these tariffs vary with the peak, off-peak and valley periods of the 24 h of the time slot. Second, incentives based programmes such as direct load control (DLC) and emergency DR programmes (EDRP) are suggested for the industrial and commercial participants. In these programmes, incentives and sometimes penalties are the part of DR which motivate the consumers for adjusting the consumption as directed by the utility. Table 3 shows the economic benefits of participating consumers comparing the cost of energy consumption with the base case when no DR is applied. In this paper, penetration of DR is considered to be 10%. After applying the different DRPs, modified demand and minimum bus voltage are determined for each load profiles are shown in Figs. 2–7. The performance of the existing DN is further enriched by using the best combination of DRPs for different feeders. Various scenarios are used for the proposed system and their outcomes are shown in the below section.

4.1 Scenario 1

Scenario 1 represents the base case considering the existing pricing mechanism of some states (sectors) of the Indian electricity market which fundamentally focuses on the collection of generation and service cost [3]. However, this subsidised and fixed tariff does not motivate the end users for efficient utilisation of electricity. Dynamically adding price component with existing tariffs may help to shift the end user's power consumption for getting the incentive benefits or even minimise the real-time imbalances. Base case tariff for different consumers' uses is shown in Table 2. Fig. 1 shows the different load factors initially used for the power flow analysis of the 33-bus network. It is noted that among the different feeders groups of consumers F-15, F-29 and F-33 are having the minimum voltages as 0.928, 0.935 and 0.932 pu, respectively.

Figs. 3–5 show that base cases have maximum peak demand values as 60, 120 and 60 kW, respectively. Table 3 shows that the highest energy consumption costs for the mentioned effected feeder (EF) consumers which are not participating in the DR programmes are ₹4194, ₹12,129 and ₹5863.2. Above indices are improved in the next scenarios by implementing the different DRPs.

Table 1 Benchmark 33-bus test system data

Particulars	Values
base voltage	12.66
nominal active demand	3715
nominal reactive demand	2300
residential feeders	1–15
industrial feeders	22–29
commercial feeders	16–21, 30–33

4.2 Scenario 2

As residential consumers of the considered network are dedicated to the feeders 1–15 as shown in Table 1. Fig. 1 indicates that the minimum voltage of respective EF is improved from the base case, which is from 0.928 to 0.944 pu and it is almost the same for all the applied DRP of this group. However, maximum peak is reduced in case of CPP which is 10% equal to the maximum considered penetration of DR. According to Table 3, RTP is providing the maximum profit for the consumer. Distribution companies' (DISCOM) main focus is to maintain the power balance and to manage the decided frequency band to avoid the restriction from the grid control area for withdrawal of energy. It can be seen from the results that residential consumers having sufficient potential for maintaining the technical constraints of the network if appropriate DRP is selected in comparison with the base case.

4.3 Scenario 3

Incentive-based DR is used for the commercial and industrial consumers for reducing the peak demand. Although, for the industrial consumer, ₹7 is the fixed base price and incentive or penalty is added to this fixed price as shown in Table 2. Voltage improvement of EF is from 0.935 to 0.941 for preferring the EDRP as shown in Fig. 6. Maximum and minimum peak reduction is 10

Table 2 DR tariff data

Types of consumers	Programmes types	Electricity tariffs, ₹/kWh	Incentives, ₹/kWh	Penalty, ₹/kWh
residential group	base case	₹6 flat rate	0	0
	TOU	−2, 3, 12 at valley, off-peak and peak periods	0	0
	CPP	13 at 20, 21, 22 h	0	0
	RTP	−4, −1, −3, 5, 3, 12.7, 3 for different intervals of 24 h	0	0
industrial and commercial groups	base case	₹7 flat rate	0	0
	DLC	7	20	0
	EDRP	7	30	0
	Interruptible and curtailed (I/C)	7	15	10

Table 3 Economic comparison of different consumer groups

Types of consumers	Programmes	Energy consumption cost, ₹	Incentives, ₹	Penalty, ₹	Supplier revenue, ₹	Consumer benefits, ₹
residential group	Base	4194	0	0	4194	—
	TOU	3827.39	0	0	3827.39	366.608
	CPP	4011.28	0	0	4011.28	182.72
	RTP	3261.88	0	0	3261.88	932.12
industrial group	Base	12,129.6	0	0	12,129.6	—
	DLC	11,297.85	2376.41	0	8921.4	3208.1
	EDRP	10,881.98	5346.92	0	5535.05	6594.5
	I/C	11,089.92	2227.88	792.13	9654.17	2475.4
commercial group	Base	5863.2	0	0	5863.2	—
	DLC	5461.1	1148.7	0	4312.4	1550.7
	EDRP	5260.1	2584.5	0	2675.5	3187.6
	I/C	5360.64	1076.9	382.9	4666	1197.2

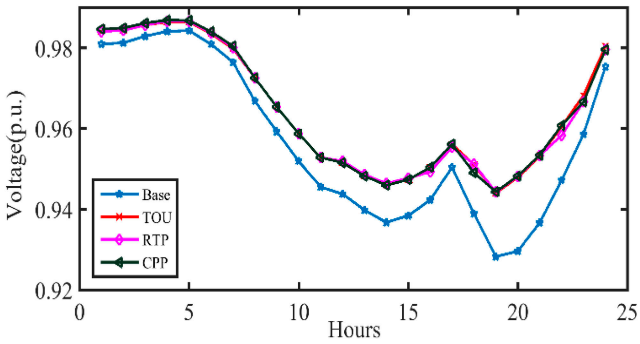

Fig. 2 *Voltage profiles for residential feeder*

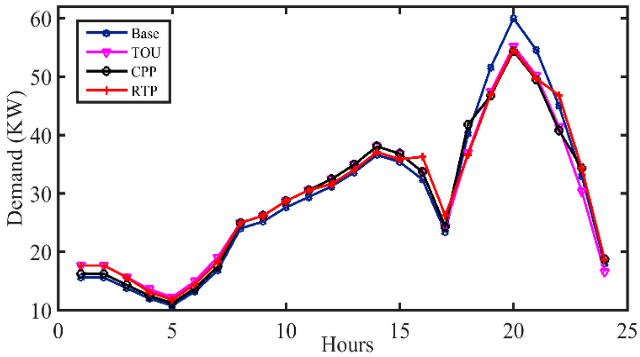

Fig. 3 *Load profiles for residential feeder*

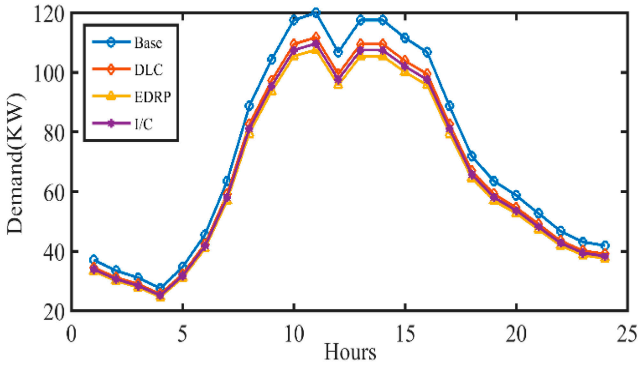

Fig. 4 *Load profile for industrial feeder*

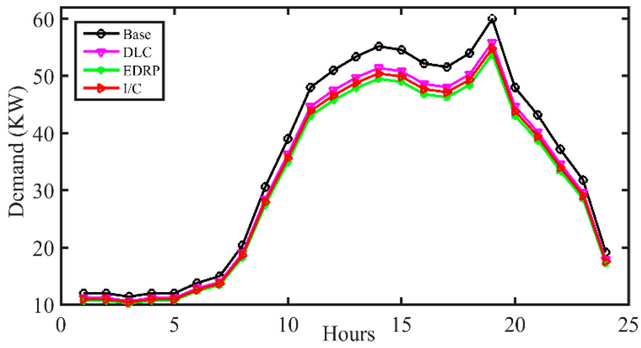

Fig. 5 *Load profiles for commercial feeder*

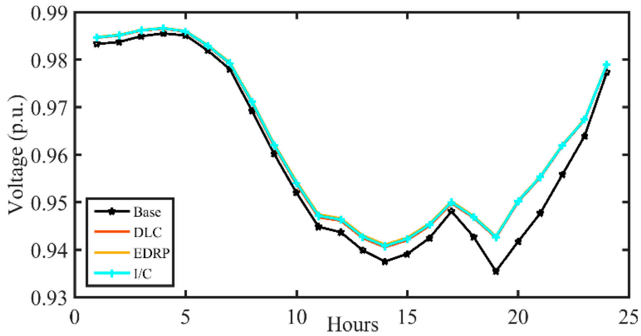

Fig. 6 *Voltage profiles for industrial feeder*

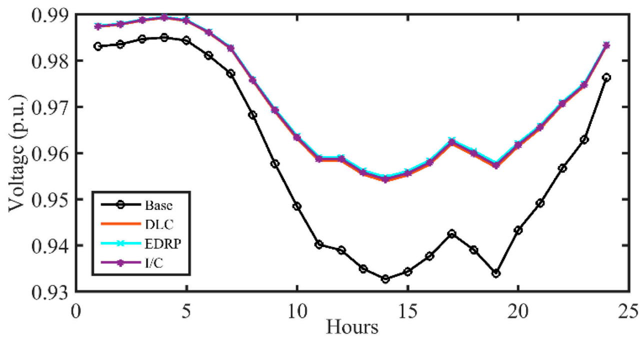

Fig. 7 *Voltage profiles for commercial feeder*

and 6.8% for floating the EDRP- and DLC-type DRPs to the EF of commercial consumers by aggregator is shown in Fig. 4. Table 3 shows that maximum economic benefits to consumers are by participating in the EDRP and least benefits for I/C DRP which are ₹6594.5 and ₹2475.4, respectively. It can be seen from the results that technical and economic improvements are achieved by implementation of DRPs in comparison with the base case.

4.4 Scenario 4

In this scenario, commercial consumer's feeder is implemented with DLC, EDRP and I/C programmes. It can be seen from Fig. 7 that voltage improvement from 0.932 pu from base case to 0.954 pu is achieved by EDRP. Technically, maximum benefits are achieved if a number of consumers adopt the EDRP. Table 2 shows that maximum incentives are offered with EDRP for peak reduction. If consumers are joining the same programmes get the benefits of ₹3187.

4.5 Scenario 5

For better network performance, the highest achieved DRP benefits for the above scenarios are implemented on EF simultaneously. RTPs for the residential EF and EDRP are implemented for the industrial and commercial EF. The system power loss of 24 h, without DRP in the base case, is 1738 kW. After DR implementation, the system power loss is reduced to 799.5 kW. The minimum node voltage of the system is improved from 0.924 to 0.955 pu when the distribution system has simply implemented the above DRP.

5 Conclusions

In this paper, the effect of multiple DRPs is investigated on three different types of consumers and utility. Comparative analysis is carried out to determine suitable DRP which results in improved voltage profile and provides economic benefits to consumer and utility both. The simulation results show that improved node voltages and peak demand reduction are obtained after implementation of DRP as compared with the base case. Residential consumer benefits in terms of energy consumption cost are maximum when their participation is more with RTP and the same is increased for industrial and commercial feeders with EDRP. Peak demand is reduced by 10% which is bounded up to maximum penetration in this paper. The proposed model also helps to reduce the limit of alternative generation used for supplying the peak generation and network congestion. DR is implemented by the aggregator model only on the feeders of the 33-bus system which is having poor voltage profile in base case condition. Voltage improvement and power loss minimisation for different EFs show that DR has the capability to enhance it with a significant margin. It is concluded that significant consumer participation with precisely defined DR tariffs with the consideration of communication technologies and proper coordination among different stakeholders provides the improved performance of the network.

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