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A Comprehensive and Preferential Analysis of Demand Response Programs

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***Abstract*— Demand Response (DR) programs are being used for a variety of load structure for reducing price/ load volatility and improving overall system reliability. This paper proposes a comprehensive and preferential review of different DR programs such as Price based DR (PBDR), Incentive based DR (IBDR) and a combination of both programs when applied to Iranian power grid with the aim of maximizing customer profit. On the basis of price elasticity of demand, a responsive economic DR model is proposed. Several DR programs are prioritized using Technique for Order Preference by similarity to Ideal Solution (TOPSIS) method and Analytical Hierarchy process (AHP) method is used for determining final priority. Independent System Operator (ISO) perspective, Utility's perspective view and Customer's perspective are considered as decision variables for final priority in AHP method and are given due weightage by entropy method.**

Keywords*— *DR, Customer benefit function, TOPSIS, AHP

Nomenclature

i	i^{th} period
j	j^{th} period
p	p^{th} alternative
q	q^{th} attribute
$I(i)$	Incentive in i^{th} hour in \$/kWh
$pen(i)$	Fine in i^{th} hour in \$/kWh
$Q_0(i)$	Base demand in i^{th} hour in kWh
$Q(i)$	Updated demand in i^{th} hour in kWh
$B_0(i)$	Income of customer at initial demand $D_0(i)$ in \$
$B(i)$	Income in i^{th} hour in \$
$C(i)$	Contract level for IBDR programs in kWh
$R_0(i)$	Base rate of electricity in \$/kWh
$R(i)$	Spot price of electricity in \$/kWh
ξ	Price elasticity of demand
D	Decision matrix
SS	Span between alternatives and perfect solution/ non-perfect solution
C	Priority measure

I. Introduction

A. Motivation and Background

The world is expanding, and so is its electricity requirement, and this requirement cannot be met by only conventional sources of energy and intermittent renewable options. Considering the uncertain and weather-dependent operation of renewable sources, the prominent solution to the power shortage problem appears to either enhance the production from already established and in use generating units or set up new generating units to meet the rapidly growing demand. As of 31 March 2022, India's net installed generation capacity was 3,99,497 MW, of which 59.1% came from fossil fuels, 39.2% from renewable sources, and 1.7% from nuclear energy [1].

With the technological advancements, the generation, transmission, and distribution of electricity may all operate more efficiently on today's grid. However with the introduction of novel energy sources, such as renewable energy sources (RES), distributed generation (DG), and microgrids (MG), the scenario for independent system operators (ISO), participants in the electricity market and the end users/customers has completely transformed [2]. Another significant problem is maintaining the necessary communication between clients and service providers for reliable and autonomous operation. Owing to the development of the smart grid (SG), which made real-time monitoring and two-way communication possible through the use of ICT and improved metering infrastructure, this issue has been resolved [3].

B. Relevant Literature

DR is one of many Demand Side Management (DSM) programmes that allows customers to shift or transfer their electrical load from peak to off-peak hours, reducing the need to expand the generation capacity of existing plants or construct new ones. Due to lower off-peak time unit costs than peak time unit charges, generation firms (GenCos) will experience financial relief, and customers will save money on their electricity bills [4]. DR programs are basically classified into two categories i.e. Price based Demand Response (PBDR) programs and Incentive based Demand Response (IBDR) [6].

1) Price based Demand Response (PBDR): The main objective of PBDR programs is to flatten load curve by reducing electricity consumption from peak hours to off-peak hours via offering low rates during off-peak hours [7]. PBDR is advantageous from both a utility and customer perspective since it gives customers the chance to actively participate in the supply-demand cycle, ensuring the stability of the system. PBDR programs are further classified into three sub-programs i.e. Time of Use (TOU) programs, Real Time Pricing (RTP) programs and Critical Peak Pricing (CPP) programs [8],[9],[10].

2) Incentive based Demand Response (IBDR): IBDR programs are designed to incentivise customers when they shift their load during the time of peak demand. By participating in these programs customers are offered certain incentives or reduction in their electricity bill [11]. IBDR programs are categorized into three basic programs i.e. Voluntary programs, Mandatory programs and Market clearing programs [12] which are further classified into Direct load control (DLC), Emergency Demand Response program (EDRP), Capacity Market Program (CAP), Interruptible/ Curtailable (I/C) Services, Demand Bidding/ Buyback (DB), Ancillary Services (A/S) Markets [13].

II. Economic Modelling of DR Programs

A. Price Elasticity of Demand

Price elasticity of demand is defined as relative change in demand with respect to relative change in price [15].

$$\xi(i,j)=\frac{\partial Q(i)}{\partial R(j)}*\frac{R_0(j)}{Q_0(i)} \quad i,j\ = 1, 2, 3\ldots.24 \tag{1}$$

For $i=j$, $\xi(i,j)\le 0$

This elasticity is known as self-elasticity and is valid for single period sensitivity loads.

For $i\neq j$, $\xi(i,j)>0$

This elasticity is known as cross-elasticity and is valid for multi period sensitivity loads.

For a 24-hour period, 24*24 Elasticity matrix can be formed using self and cross elasticity coefficients as shown below [6].

$$\begin{bmatrix}\Delta Q(1)\\ \Delta Q(2)\\ \Delta Q(3)\\ \ldots\\ \Delta Q(24)\end{bmatrix}=\begin{bmatrix}\xi(1,1) & \xi(1,2) & \ldots & \ldots & \xi(1,24)\\ \xi(2,1) & \xi(2,2) & \ldots & \ldots & \ldots\\ \ldots & \ldots & \xi(i,j) & \ldots & \ldots\\ \ldots & \ldots & \ldots & \ldots & \ldots\\ \xi(24,1) & \ldots & \xi(24,j) & \ldots & \xi(24,24)\end{bmatrix}*\begin{bmatrix}\Delta R(1)\\ \Delta R(2)\\ \Delta R(3)\\ \ldots\\ \Delta R(24)\end{bmatrix} \tag{2}$$

Diagonal elements i.e. $\xi(1,1)$, $\xi(2,2)$ …denotes self-elasticity whereas $\xi(1,2)$, $\xi(2,1)$ …denotes cross elasticity.

B. Modelling of elastic load

Assuming a consumer changes his demand pattern from Base demand $Q_0(i)$ to new demand $Q(i)$, then variation in demand is given by

$$\Delta Q(i)=Q(i)-Q_0(i) \tag{3}$$

If consumer is enrolled in IBDR program then he is liable to get incentives as per the contract. If $I(\mathrm{i})\$$ is the incentive value that is given to the consumer in i^{th} hour for each KWh reduction then net incentive paid to consumer is

$$INC(\Delta Q(i))=I(i).\Delta Q(i) \tag{4}$$

For disobeying the contract regulation customer will face fine, let contract agreement for the i^{th} hour is *C(i)* and fine for i^{th} hour is $pen(i)$, then total fine is given by

$$PENALTY(\Delta Q(i))=pen(i).[C(i)-\Delta Q(i)] \tag{5}$$

Let us assume that $B(Q(i))$ is the income of consumer in i^{th} hour by using $Q(i)\,KWh$, then consumer net profit in i^{th} hour is given by

$$PRO(\Delta Q(i))=B(Q(i))+INC(\Delta Q(i))-Q(i)R(i) - PENALTY(\Delta Q(i)) \tag{6}$$

For maximum customer benefit function, differentiation of Eq. 6 with respect to *Q(i)* should be equal to zero i.e.

$$\frac{\partial PRO(\Delta Q(i))}{\partial Q(i)}=\frac{\partial B(Q(i))}{\partial Q(i)}+\frac{\partial INC(\Delta Q(i))}{\partial Q(i)}-R(i) - \frac{\partial PENALTY(\Delta Q(i))}{\partial Q(i)}=0 \tag{7}$$

After differentiating individual terms we get,

$$\frac{\partial B(Q(i))}{\partial Q(i)}=R(i)+I(i)+pen(i) \tag{8}$$

The customer benefit function is expanded using Taylor's series expansion method and is given by

$$B(i)=B_0(i)+R_0(i)\{Q(i)-Q_0(i)\}.[1+\frac{Q(i)-Q_0(i)}{2\xi(i)Q_0(i)}] \tag{9}$$

Differentiating above equation and put resulted values in equation (8), we get

$$R(i)+I(i)+pen(i)=R_0(i).[1+\frac{Q(i)-Q_0(i)}{2\xi(i)Q_0(i)}] \tag{10}$$

So, updated demand should be equal to

$$Q(i)=Q_0(i)\{1+\xi(i,i).\frac{[R(i)-R_0(i)+I(i)+pen(i)]}{R_0(i)}\} \tag{11}$$

Equation (11) is valid for self-elastic load, for cross-elastic load this equation gets converted to

$$Q(i)=Q_0(i)\left\{1+\sum_{\substack{i=1\\ i\neq j}}^{24}\xi(i,j).\frac{[R(j)-R_0(j)+I(j)+pen(j)]}{R_0(j)}\right\} \tag{12}$$

Net response of elastic load modelling is given by

$$Q(i)=Q_0(i)\left\{\begin{array}{l}1+\xi(i,i).\dfrac{[R(i)-R_0(i)+I(i)+pen(i)]}{R_0(i)}\\ +\displaystyle\sum_{\substack{j=1\\ j\neq i}}^{24}\xi(i,j).\dfrac{[R(j)-R_0(j)+I(j)+pen(j)]}{R_0(j)}\end{array}\right\} \tag{13}$$

III. Methodology Used for Sorting of Programs

For prioritizing of different DR programs (DR alternatives), few DR attributes such as reduction in peak demand, consumption of energy, load factor, peak to valley (P2V) distance and total bill of consumer are selected and based on the weightage assigned by entropy method these programs are given preference by TOPSIS method according to ISO, Customer and utility point of view. Final priority is given by using Analytical Hierarchy Process (AHP) method considering regulator point of view.

A. Entropy method

Entropy method is used for uncertainty allocation in decision making. For any distribution function, a decision matrix can be formulated as [16].

$$D = \begin{bmatrix} X_{11} & \dots & X_{1n} \\ \dots & \dots & \dots \\ X_{m1} & \dots & X_{mn} \end{bmatrix} \quad (14)$$

In the D matrix rows represents alternatives and columns represents attributes, component X_{pq} represents performance of the p^{th} alternative and q^{th} attribute, here

$p \subseteq m \,, q \subseteq n$

Elements of above matrix can be normalized as

$$P_{pq} = \frac{X_{pq}}{\sum_{p=1}^{m} X_{pq}} \quad (15)$$

Entropy value of each element can be obtained as

$$E_q = -\frac{\sum_{q=1}^{n} P_{pq} . \ln P_{pq}}{\ln n} \quad (16)$$

The range of entropy value calculated is [0,1]. Weight of each attribute W_q can be calculated as

$$W_q = \frac{1 - E_q}{\sum_{q=1}^{n} 1 - E_q} \quad (17)$$

For several point of view different, different importance factors are assigned and improved weights are given by

$$IW_q = \frac{\lambda_q * 1 - E_q}{\sum_{q=1}^{n} \lambda_q * 1 - E_q} \quad (18)$$

Lower values of weights indicates negligible importance of attributes for alternatives and vice versa.

B. *TOPSIS method*

In TOPSIS method, span between each alternative and perfect & non-perfect solution is calculated. It is obvious that for ideal solution distance should be minimum and for non-ideal solution it should be maximum [17].

$$r_{pq} = \frac{X_{pq}}{\sqrt{\sum_{p=1}^{m} X^2_{pq}}} \quad (19)$$

Weighted normalised matrix D can be calculated as

$$V_{pq} = W_q * r_{pq} \quad (20)$$

Now finding the best solution matrix for positive and negative perfect solution,

$$A_q^+ = (\max V_{pq} \left| q \in q^+ \right|, \min V_{pq} \left| q \in q^- \right|) \qquad p = 1, \dots m$$

$$A_q^- = (\min V_{pq} \left| q \in q^+ \right|, \max V_{pq} \left| q \in q^- \right|) \qquad p = 1, \dots m$$

(21)

Next step calculates the span between each alternative and perfect & non-perfect solution

$$SS_p^+ = \sqrt{\sum_{q=1}^{n} (\mathrm{V}_{pq} - \mathrm{V}_q^+)^2} \qquad p = 1, \dots m \quad (22)$$

$$SS_p^- = \sqrt{\sum_{q=1}^{n} (\mathrm{V}_{pq} - \mathrm{V}_q^-)^2} \qquad p = 1, \dots m \quad (23)$$

Finding the performance score of each alternative as follows

$$C_p = \frac{SS_p^-}{SS_p^+ + SS_p^-} \quad (24)$$

IV. NUMERICAL STUDIES

For evaluation of attributes and portfolio-sorting load curve of Iranian power grid has been used for simulation [18]. Fig. 1 represents the load variation which has valley (V) period (12 am to 7 am), off-peak (O-P) period (7 am to 18 pm) and peak (P) period (18 pm to 24 pm). Several DR programs are considered in this paper and are divided into three class: Class 1 contains four PBDR programs i.e. TOU, CPP, RTP and (TOU+CPP). Class 2 contains four IBDR programs i.e. DLC, EDRP, CAP and I/C programs. Class 3 contains a combination of Program 1 and Class 2 programs. TABLE I represents the corresponding price elasticity values of demand [18].

TABLE I. SELF AND CROSS ELASTICITIES.

	valley	off-peak	peak
valley	-0.1	0.01	0.012
off-peak	0.01	-0.1	0.016
peak	0.012	0.016	-0.1

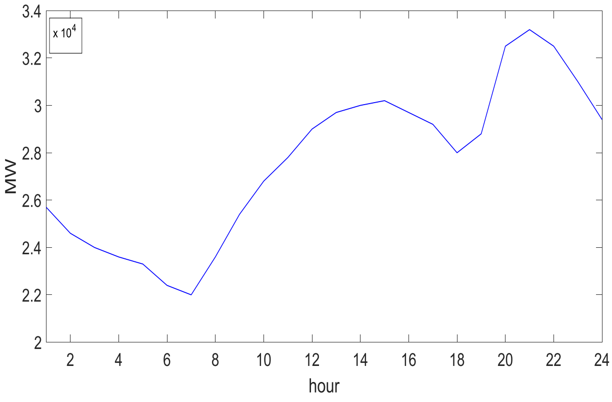

Fig. 1. Iranian Peak load curve on 28/08/2007.

TABLE II shows the various DR alternative programs and their corresponding prices, incentives and penalties. New demand for each program alternative is shown in Fig. 2-4.

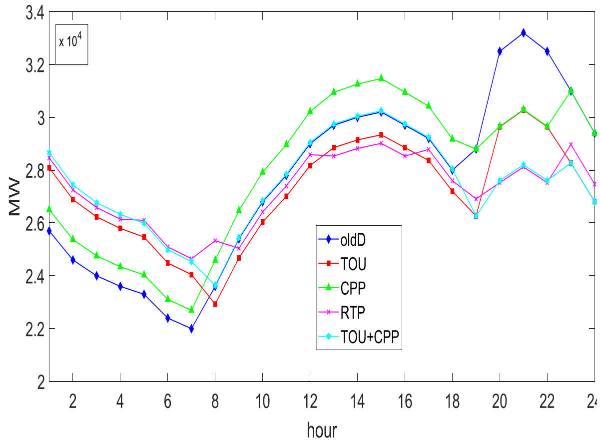

Fig. 2. Effect of PBDR on load variation.

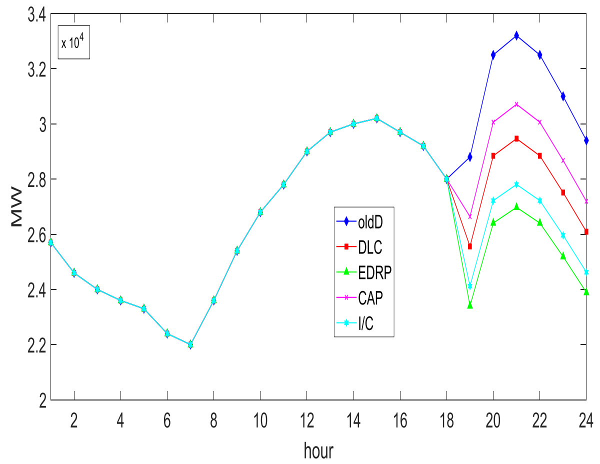

Fig. 3. Effect of IBDR on load variation.

Fig. 2 indicates the effect of PBDR programs on the load characteristics whereas from Fig. 3 it is clearly understood that the changes in load curve occurs only during peak time. Fig. 4 shows the effect of Class 3 programs.

A. Analysis of the results

Economic parameters considered are payable bill of customer, DR incentive, DR fine, monetary revenue of utility and benefit of consumer whereas technical parameters considered are peak value of load, reduction in peak demand, consumption of energy, reduction in total energy consumed, load factor and peak-to-valley (P2V) distance. Corresponding results are shown in TABLE III and TABLE IV.

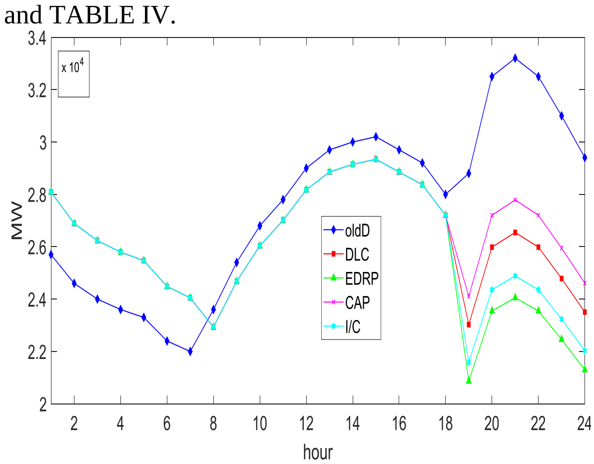

Fig. 4. Effect of PBDR+IBDR on load curve.

TABLE II. DR PROGRAM PORTFOLIO

Case	Electricity Price ($/KWH)	Inc ($/KWH)	Pen ($/KWH)
Base	160 flat	0	0
1	40, 160, 200 at V, O-P and P slot respectively	0	0
2	300 at 20, 21, 22 hr	0	0
3	40, 40, 40, 40, 20, 20, 20, 20, 160, 160, 160, 160, 200, 200, 200, 200, 160, 160, 160, 300, 300, 300, 160, 160 at 1-24 hr respectively	0	0
4	40, 160, 200 at V, O-P and P slot respectively and 300 at 20, 21, 22 hr	0	0
5	160 flat	180	0
6	160 flat	300	0
7	160 flat	80	40
8	160 flat	180	80
9	40, 160, 200 at V, O-P and P slot respectively	180	0
10	40, 160, 200 at V, O-P and P slot respectively	300	0
11	40, 160, 200 at V, O-P and P slot respectively	80	40
12	40, 160, 200 at V, O-P and P slot respectively	180	80

*Inc-Incentive, Pen-Penalty

TABLE III. MONETARY DATA OF DR PROGRAMS

Case	CB ($\times 10^6$ $)	Inc ($\times 10^6$ $)	Pen ($\times 10^6$ $)	Rev ($\times 10^6$ $)	BC ($\times 10^6$ $)
Base	105984	0	0	105984	0
1	89514	0	0	89514	16469
2	120068	0	0	120068	-14084
3	93845	0	0	93845	12138
4	98263	0	0	98263	7720
5	102610	3794	0	98815	7168
6	100362	10541	0	89820	16163
7	103735	1124	187	102798	3185
8	101111	5481	-937	94693	11290
9	85298	6763	0	78535	27448
10	82487	15488	0	66998	38985
11	86703	2443	-472	83787	22196
12	83424	8449	-2256	72718	33265

*CB-Customer Bill, BC-Benefit of customer, Rev-Revenue

TABLE IV. TECHNICAL COMPARISION OF DR PROGRAMS

Case	Peak (MW)	PRD (%)	ENC (MWh)	ERD (%)	LF (%)	P2V (MW)
Base	33200	0	662400	0	83.1	11200
1	30278	8.8	652491	1.5	89.7	7351
2	31468	5.2	672018	-1.45	88.9	8775
3	29014	12.6	654888	1.13	94.0	4369
4	30245	8.9	659362	0.46	90.8	6609
5	30200	9.04	641317	3.18	88.4	8200
6	30200	9.04	627262	5.3	86.5	8200
7	30710	7.5	648345	2.12	87.9	8710
8	30200	9.0	631947	4.6	87.1	8200
9	29339	11.6	631409	4.68	89.6	6411
10	29339	11.6	617354	6.8	87.6	8473
11	29339	11.6	638436	3.62	90.6	6411
12	29339	11.6	622039	6.09	88.3	7753

*ENC-Energy Consumption, P2V-Peak to Valley, LF-Load Factor, PRD-Peak Reduction, ERD-Energy Reduction

V. PRIORITISING OF DR PROGRAMS

A Decision matrix *D* is formed by selecting few attributes as mentioned above from TABLE III and TABLE IV using Eq. 14. These attributes are then assigned weights by entropy method using Eqs. 15-17 and are shown in TABLE V. It is observed that highest priority has been given to attribute named peak reduction and lowest priority has been given to attribute named load factor.

TABLE V. WEIGHT OF ATTRIBUTES

Attribute	PRD	ENC	LF	P2V	CB
Weights	0.52	0.0066	0.0052	0.33	0.13

TABLE VI. IMPROVED WEIGHTS (AS PER ISO)

Attribute	PRD	ENC	LF	P2V	CB
Weights	0.57	0.0024	0.0038	0.36	0.047

TABLE VII. IMPROVED WEIGHTS (AS PER UTILITY)

Attribute	PRD	ENC	LF	P2V	CB
Weights	0.34	0.0043	0.0069	0.21	0.42

TABLE VIII. IMPROVED WEIGHTS (AS PER CUSTOMER)

Attribute	PRD	ENC	LF	P2V	CB
Weights	0.34	0.0087	0.0034	0.21	0.42

A. *Improved Weights: As per ISO*

From ISO point of view reduction in peak value and P2Vdistance has got the highest importance and other attributes have relatively lower importance.

$$\lambda_n = \{0.3, 0.1, 0.2, 0.3, 0.1\}$$
$$\sum \lambda_n = 1$$

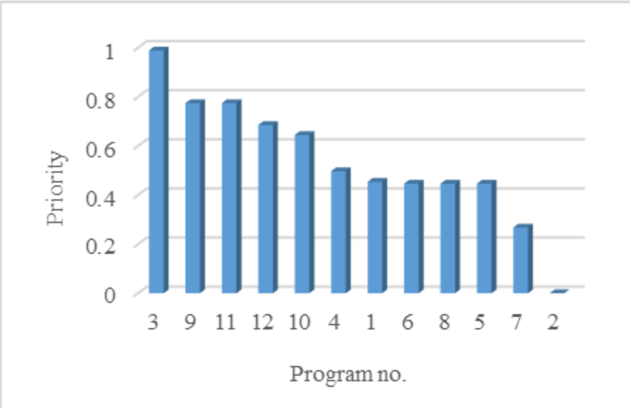

Fig. 5. Priority of DR Alternatives (As per ISO)

Improved weights have been calculated using Eq. 18 and are shown in TABLE VI, then by using TOPSIS method (Eqs. 19-24) priority of programs has been calculated and the results are shown in Fig. 5.

B. *Improved Weights: As per Utility*

From Utility point of view customer bill has been given the highest importance, load factor is assigned second highest importance and other attributes have relatively lower importance.

$$\lambda_n = \{0.1, 0.1, 0.2, 0.1, 0.5\}$$
$$\sum \lambda_n = 1$$

Improved weights are shown in TABLE VII and corresponding results of the above analysis using TOPSIS method has been shown in Fig. 6.

C. *Improved Weights: As per Customer*

From Utility point of view customer bill has been given the highest importance, energy consumption is assigned second highest importance and other attributes have relatively lower importance.

$$\lambda_n = \{0.1, 0.2, 0.1, 0.1, 0.5\}$$
$$\sum \lambda_n = 1$$

Based on above analysis, from customer point of view, improved weights are shown in TABLE VIII and priority of the programs has been shown in Fig. 7.

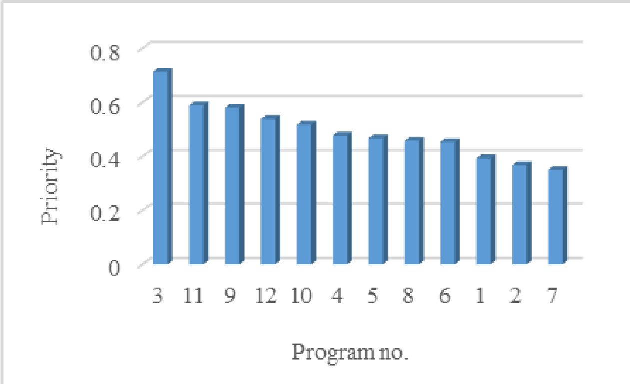

Fig. 6. Priority of DR Alternatives (As per Utility)

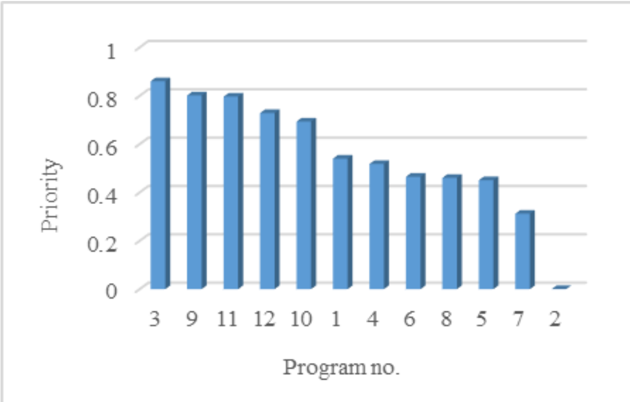

Fig. 7. Priority of DR Alternatives (As per Customer)

D. *Final Priority: As per Regulator*

DR programs have been prioritized based on ISO, Utility and Customer point of view, now its regulator's turn to assign weights to these entities using AHP method. As per regulator/ stakeholder, ISO has been assigned highest weight and utility is assigned least weight as shown in TABLE IX. Based on this analysis final priority has been given and is shown in Fig. 8.

TABLE IX. FINAL WEIGHTS (AS PER REGULATOR)

	ISO	Utility	Customer	Weights
ISO	0.57	0.57	0.57	0.57
Utility	0.14	0.14	0.14	0.14
Customer	0.29	0.29	0.29	0.29

VI. RESULTS

It is observed that load characteristic changes its behaviour based on the DR program. In Price based DR program there is change in demand at almost every hour of day whereas in Incentive based DR program changes are observed during peak period only as incentive and penalty are effective during peak demand period only. It is clear from Fig. 8 that PBDR program (case 3) has the highest priority and PBDR+IBDR programs have subsequent priorities and rest of the programs follows the list. Based on this procedure of portfolio analysis DR stakeholders can maximize their interests and achieve technical and economical efficiency.

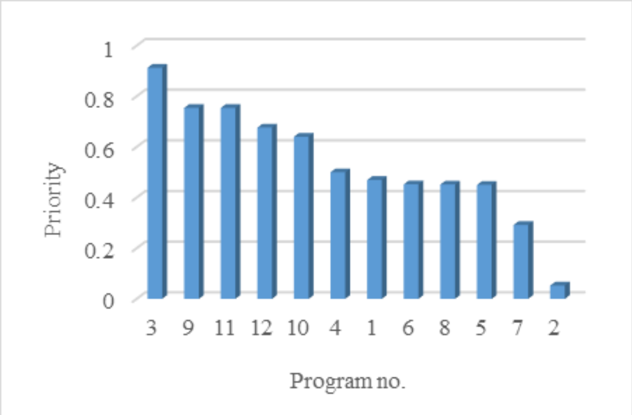

Fig. 8. Final Priority of DR Alternatives (As per Regulator)

VII. Conclusion

In this paper a comprehensive and preferential analysis of several DR programs is presented and it is shown that consumer's electricity demand depends not only on price but also on elasticity of demand, incentives and penalties/ fine. Prioritizing of programs using TOPSIS method along with AHP method gives an option to ISO, Utility, Customer and Regulator to choose best program based on their preferences.

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