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Responsive Demand in Networks with High Penetration of Wind Power

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Abstract—The value of renewables is significantly affected by their penetration, concentration and location. Value is further affected by the responsiveness of demand which will reduce the need for back up power through non-renewable sources. By increasing the penetration of renewables in power systems, demand side participation become more important. Demand Side Management (DSM) programs have been studied for a long time and among all DSM programs Responsive Demand seems to be the most applicable type of DSM for a system with significant intermittent generation. It mitigates issues such as required reserve, network congestions and higher/lower voltage profiles and thus results in less operation cost although little attention has been made to quantify the benefits of responsive demand. In this paper, the value of wind generation without responsive demand is quantified first, by introducing responsiveness in the demand side, the reduction in operation cost is calculated and the additional benefits are quantified. The quantification was evaluated on the IEEE 30 busbar system through Security Constraint Unit Commitment (SCUC) and the results indicate the benefits of responsive demand on operational and environmental characteristics in power system.

***Index Terms*--Dynamic Demand, Value of Wind, Demand Side Management, Generation Scheduling, Responsive Demand**

I. NOMENCLATURE

$C(c,e,s)$	Objective function (cost, emission and security)
I	Number of generation unit
P	Scheduled power for unit i
Si	Security violation
αs	Scaling security factor
αc	Scaling cost factor
αe	Scaling emission factor
τs	Boolean variable for security
τc	Boolean variable for production cost
τe	Boolean variable for emission
FCi	Fuel cost
MCi	Maintenance cost
STi	Start up cost
SDi	Shut down cost
BMi	Base maintenance cost
IMi	Incremental cost
$\alpha i, \beta i, c$	Cost coefficients
TSi	Turbine start up cost
BSi	Boiler start up cost
MSi	Start up maintenance cost
Di	Number of hours down
ASi	Boiler cool down coefficient
K	Incremental shutdown cost
$\alpha, \beta, \gamma, \delta, \varepsilon$	Emission coefficients
Sv	Voltage security violation
Sg	Generator reactive power security violation
τv	Voltage Boolean variable
τb	Branch flow Boolean variable
τg	Generator re-power Boolean variable
$CSPPi$	Capacity Limit of Unit i to provide Spinning Reserve
SPi	Maximum contribution of unit i to spinning reserve
Sb	Branch power flow security violation

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II. INTRODUCTION

Issues associated with the integration of wind power into power system have been characterized as either engineering issues, operational issues or planning issues [1].

Engineering issues include harmonics, reactive power supply and voltage regulation, frequency control, fault level, island operation.

Operational issues include the effect of intermittent power output into non-intermittent (conventional) networks, operating reserve requirements, unit commitment and economic dispatch.

Planning issues concern the appropriate modeling and evaluation of intermittent wind resources compared to conventional resources.

An accurate quantification of the economical benefits of renewable generation is of supreme importance considering the strategies set out in order to mitigate above issues. Value of Renewable Penetration is a term which deals with this concept and several researchers in the past have evaluated the value of renewables in different networks as well as identifying the barriers to increase this value [2], [3], and [4]. If any renewable unit is to be integrated into any power system it needs to be considered in unit commitment problem in that system to evaluate the effect of injecting power through renewable units on the whole network and to calculate the total energy production cost with respect to several objectives; cost, emission and security [5].

In the process of solving the unit commitment problem, intermittent generation units have some constraints; such as ramp-rate constraint for generation scheduling and for reserve activation like conventional plants as well as their most significant character; intermittency. In addition integrating high level of renewables has implications for the planning and operation of transmission system and sometimes fails to extract the full output of renewables because of transmission congestion.

In other word high penetration of renewables in the network will further push the transmission tie-lines to their power transfer limits and cause problems such as network congestion, voltage security or even voltage stability where the network is already under stressed due to the uncertainty of generation and demand and power market transactions [6] i.e. voltage rise happens in rural areas with high penetration of renewables and low demand; again this is mainly because of the traditional structure of the network which may not accommodate additional power [7, 8].

Although, one effect of increasing the proportion of embedded generation will be to reduce the flow across the interface between the transmission and distribution networks and this will tend to delay the need for reinforcement of parts of the transmission network, but it is unlikely to remove the need for the substations that exist at the interface between the transmission and distribution systems (i.e. the Grid Supply Points). These will continue to be required to balance the fluctuations between generation and demand in that specific part of the distribution network from minute to minute.

The traditional solution to mitigate intermittency is to back up renewable units with other sources of power either through running units or by energy storage devices. However the only solution to mitigate the issues with regarding to the network is to invest in network reinforcement.

Demand Side Management (DSM) Programs have been used for a long time for different purposes such as increasing the efficiency of the power system and saving the energy. Economy 7 and Economy 10 are the most widespread type of DSM programs in the UK which by shifting the demand will reduce the peak demand and the need for running the peak time running units which are usually expensive units will be eliminated. The current DSM methods which shift the demand could benefit system with renewables but not in terms of mitigating the intermittency issues because power fluctuation may happen at any time therefore demand shifting methods can not solely be a solution for intermittency.

One of the stand of the art types of DSM; Dynamic Demand (Responsive Demand) is being used in US to provide ancillary services in particular spinning reserve [9]. Dynamic demand is a type of load which is flexible and is ready to be shed if a network needs extra power. This type of demand usually includes passive loads such as air conditioning, water heating and refrigerators which if turned off upon to request by the network operator, do not cause difficulty for consumers.

The problem with existing methods is that they only consider the benefits which could be achieved in short term in terms of improving the efficiency of the power system and none of them deeply considers the effects of implementing these methods in much wider aspect which usually requires more investment and may benefit whole the system in long term. Demand is actually the first object of power system and all reliability and investment analyses of the network is being done by considering the demand as end point of the system which must be supplied. Through this method demand could be managed to benefit the whole the system such as other objectives at the distribution level; i.e. transmission congestion which stops network to accommodate more power and requires more investment to expand it.

In an intermittent environment the value of wind is one of the most important objectives which needs to be studied well before any investment in building and installing windfarms, as in terms of cost it basically represents the amount saved per MW through adding the new windfarm.

In this research project we have demonstrated a system with both conventional plant and intermittent unit. We run our simulation; first without any DSM program and get technology specific characteristics of the system such as production cost, security and emission and calculate the value of wind. Then by introducing Responsive Demand in the domestic Sector we aim to shift their consumption to off peak and especially when output of windfarms is not adequate and compare the outcomes of this case with the previous case.

III. Assessment Frame Work

Unit commitment is used in this research project as an assessment tool to determine the value of wind with and without responsive demand.

The aim of the Security-Constrained Unit Commitment (SCUC) problem is to find the hourly generation, reserves and price sensitive load schedule that minimizes the sum of energy costs, reserve costs and the negative of revenue from price-sensitive load over a twenty-four hour period subject to meeting all the network security constraints such as apparent power flow constraints, generator reactive power output constraints and voltage in busbars. SCUC is being considered more and more recently because Security of supply is one of the major concerns of network operators.

Security Constrained Unit Commitment aims to minimize $C(c,e,s)$ and increase the security (through minimizing the security violation indexes) in a scheduling period with regarding to Production cost *"c"* ,Emissions *"e"* and Security violation index *"s"*:

A. Objective function

$$Min\,C(c,e) = (\sum_{i=1}^{N}[\tau c.\alpha c.c(Pi) + \tau e.\alpha e.e(Pi)] + \tau s.\alpha s.s) \quad (1)$$

B. Generation cost

$$c(Pi) = FCi\,(Pi) + MCi\,(Pi) + STi\,(Pi) + SDi\,(Pi) \quad (2)$$

C. Fuel cost

$$FCi\,(Pi) = \alpha i.Pi^{2} + \beta i.Pi + ci \quad (3)$$

D. Maintenance cost

$$MCi\,(Pi) = BMi + IMi\,.Pi \quad (4)$$

E. Start up cost

$$STi = TSi + [1 - e^{(Di\,/\,ASi)}].BSi + MSi \quad (5)$$

F. Shut down cost

$$SDit = KPi \quad (6)$$

G. Emission Function

$$e(Pi) = \alpha . Pi^{2} + \beta Pi + \gamma + \delta . e^{\varepsilon . Pi} \quad (7)$$

H. Security Function

The Security function consist of 3 main objectives; voltage as busbars, apparent power flow in branches and reactive power generated by generation units:

$$s = \tau v . sv + \tau b . sb + \tau g . sg \quad (8)$$

I. Voltage Security Violation

This is a term which deals with the voltage at bus bars which must always remain between a minimum and maximum limit at all the scheduled generation period:

J. Apparent Power Flow

Apparent flow (Complex power; $S = P + jQ$) in transmission lines is one of the constraints which sometimes cause decomitting a unit or keeping its output up to certain level as transmission lines are running up to their maximum capacity; some thing which is known as transmission congestion.

K. Reactive Power generated by units

In power systems voltage collapse usually happens when the reactive power is not enough to meet inductive loads such as induction motors etc. Generation units generate certain amount of reactive power and exceeding this limit will reduce the security of supply.

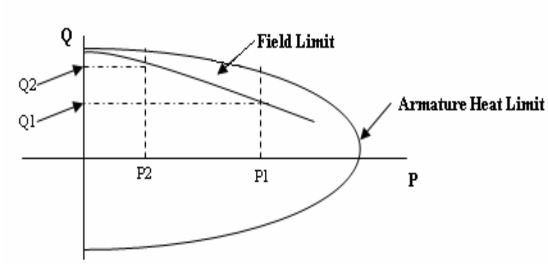

Fig 1. Generator Power Output Capability Graph.

Other constraints:

Apart from those mentioned objective constraints during unit commitment, there are several other constraints which must be considered:

L. Crew constraints:

With thermal power plants, particularly starting up and shutting down generation units needs a certain number of crews to operate and sometimes because of lack of crews it is impossible to start up or shut down more than one unit at a time.

M. Minimum up and down time:

In some plants i.e. nuclear, hydrothermal etc, because of economic efficiency and technical constraints it is impossible to shut down a unit before a certain duration of being in duty is reached; again once a unit is turned off it may be impossible to start it up and bring it back to network before certain number of hours of being off-duty is reached. These units have different characteristic than “Peaker” units; for instance gas turbine units which usually are not subject to a minimum up and down time and can start up and supply peak demand and shut down straight after peak period.

N. Generator output limits

Generation units must be scheduled to operate within their maximum and minimum rated output in terms of active and reactive power:

$$PGi\min \leq PGi \leq PGi\max \qquad QGi\min \leq QGi \leq QGi\max \quad (9)$$

O. Spinning Reserve

Total Generated power in the system must meet demand, network losses and required Spinning Reserve. Spinning reserve is the amount of power always available to be dispatched in the system to meet sudden demand increase or being used in minor contingencies.

$$\sum_{i=1}^{N} Pi \geq Demand + Network\ looses + Spinning\ reserve \quad (10)$$

$$\sum_{i=1}^{N} (CSPPi - Pi, SPi) \geq Spinning\ reserve \quad (11)$$

P. Negative Reserve Requirement

Negative reserve is to make sure at each scheduling period there are sufficient generation units in the system which are running at certain amount higher than their minimum generation limits. This is to allow their output be reduced in case of loosing the demand in case of an event predicting it higher than actual value [10].

Q. Generator Ramping Up and Ramping Down Rate

The ability to increase (or decrease) the output power of a generator in a certain amount of time is called *Ramping Rate.* Generation units have different ramping rates and this must be considered in unit commitment. *Ramping rate* is particularly important for those units which are due to be committed to supply power reserve (especially spinning reserve) as certain amount of reserve is supposed to be generated by these units. Network operators i.e. NGC in the UK, have their own criteria for selecting units providing spinning reserve which in the UK is 25MW/minute within 2 minutes of instruction and to be sustained up to the minimum of 15 minutes [11].

R. Reliability Must Run Units (RMR)

In the power system generation units that the ISO determines are required to be on-line [at certain times] to meet applicable reliability criteria requirements [12]; such as voltage support or during system maintenances.

S. Regulatory Must Run Units (RGMR)

The main objective of regulatory must-run units is to maintain “fair” competition in a deregulated market. A good example of regulatory must-run units is hydro power plants. Most of these power plants are multipurpose units which were designed both for power generation and irrigation purposes. Allowing a hydropower plant to participate in the competitive market may defeat the agricultural purpose [12]. Another example of RGMR units exists in places where heat demand is added on top of electrical demand. In order to supply enough heat, we must make sure that enough thermal units (Combined Heat and Power CHP) which are supposed to provide heat in all heat demand areas are committed at each scheduling period.

T. Regulatory Must Take Units (RMTU)

In deregulated energy markets there are power purchase agreements (PPA) which occurred prior to the deregulation and carried over to the deregulated market. Examples of regulatory must-take units are nuclear power plants, cogenerations, and PPAs with other entities such as neighboring countries. It means in OPF, ED and UC calculations these PPAs also need to be considered [12].

U. Qualified Unit Providing Ancillary Services in Deregulated Energy Market

As mentioned in (9.5) ancillary services usually come from specific units. In deregulated energy market where price bidding exists both for power and ancillary services, not all the generation units can participate in providing ancillary services. At each period some power utilities which normally participate in providing ancillary services may or may not be available.

V. Balance between Demand and Power in Deregulated Energy Market

In a deregulated Energy market (DEG), network operators particularly those who provide ancillary services such as spinning reserve or operating reserve, are allowed to either supply an extra power into grid or by reducing the demand to reduce the need of an extra reserve. This is a new term in DEG which has been using in some parts of the world [13]. Therefore by committing those companies which are allowed to shed the load to unrequire the network to extra power, in fact the demand which needs to be supplied is being reduced and network parameters must be studied well before committing generation units as it may cause voltage rise in the system because of extra power which is not being consumed. There are also other ways such as pump storages, interchange etc. All the power which is due to be achieved from these sources must be subtracted from total required reserve [14].

IV. Implementation

A. Test System

The IEEE Standard 30 Bus Test System [15] has been chosen for our project. Figure 2 shows the proposed network, the main objective of our research is to integrate renewables into the system, after running the simulation without the presence of any wind farm, 2 wind farms step by step have been added to this system in different locations. Table 1 shows the generators cost and emissions characteristics and Table 2 shows Minimum Up Time (MUT), Minimum Down Time (MDT), Ramp rate, Minimum and Maximum power output and locations of conventional plants. All generators data apart from generator No. 9, 10 and 11 are derived from IEEE Reliability Test System RTS-96[15]. Total conventional plants capacity is 300MW while 2 windfarms have 15MW (windfarm No.1 capacity factor = 26%) and 20MW (Windfarm No.2 capacity factor = 29%) installed capacity. Figure 3 shows weekly output of two windfarms.

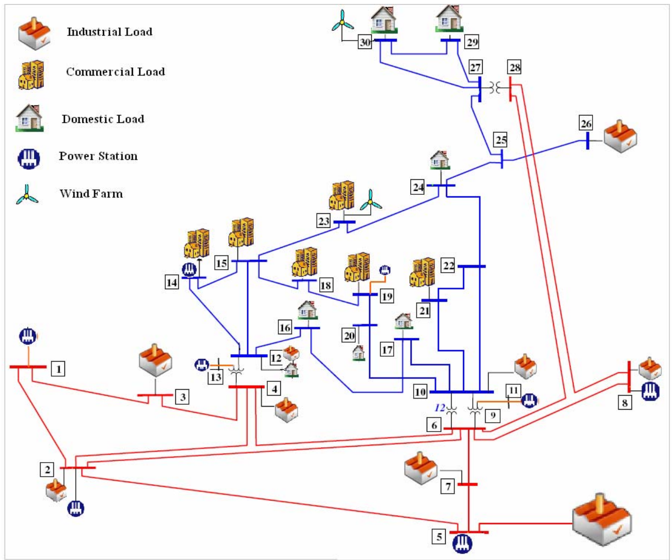

Fig 2. The IEEE 30 Bus Test System.

TABLE I
GENERATOR COST AND NOX EMISSION CHARACTERISTICS

Unit	a	b	c	α	β	γ	δ	ε
1	0.02	1.2	40	9.9E-2	-5.6E-2	4.1E-2	1.5E-4	3.86
2	0.01	0.8	38	5.6E-2	-6.1E-2	4.8E-2	1.0E-4	3.3
3	0.06	4.5	45	7.6E-2	-5.1E-2	2.6E-2	1.0E-8	8.0
4	0.01	0.4	30	3.4E-2	-3.6E-2	5.3E-2	1.0E-6	2.0
5	0.06	5.2	23	3.5E-1	-5.1E-2	2.3E-2	1.0E-8	8.0
6	0.05	2.2	42	4.4E-2	-5.1E-2	3.4E-2	1.0E-8	8.0
7	0.05	3.0	45	1.8E-1	-5.1E-2	2.9E-2	1.0E-8	8.0
8	0.04	1.8	53	5.2E-2	-9.5E-4	3.1E-2	2.3E-4	6.67
9	0.00	0.0	0	0E+0	0E+0	0E+0	0E+0	0.0
10	0.00	0.0	0	0E+0	0E+0	0E+0	0E+0	0.0

TABLE II
OTHER GENERATOR CHARACTERISTICS

Unit	MUT	MDT	Ramp Rate	P*min*	P*max*	Busbar No.
1	3	2	5	10	35	11
2	2	2	4	10	45	5
3	3	2	7	8	40	2
4	3	2	6	10	60	1
5	1	1	6	5	25	19
6	2	1	5	2	30	14
7	2	2	7	5	35	8
8	2	1	4	5	30	13
9	0	0	4	0	10	23
10	0	0	4	0	15	30

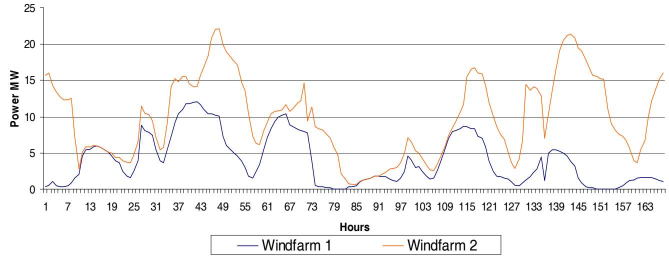

Fig 3. Weekly output variations of Wind farms.

B. Demand Data

For each period of unit commitment, load forecasting is a must and several research projects have been practicing the methods which give less error in predicting the demand which needs to be supplied [16, 17]. Failure to meet predicted demand can lead to shedding the load which can lead to severe economical and security issues. Total demand characteristic regardless of the specific type of demand varies in electric networks. There are several factors available in network policies which affect demand such as multi tariff charging method; single rate, double rate or Economy 7 (E7) and Load Factor (LF). As each sector in the system represents different electricity load patterns, then it is necessary to know which demand sectors exist in this network and which model of demand they are representing.

In this project 80% of total demand has been assumed to be domestic and it has been assumed and proportion of domestic weekly demand has a pattern which is shown in Figure 4.

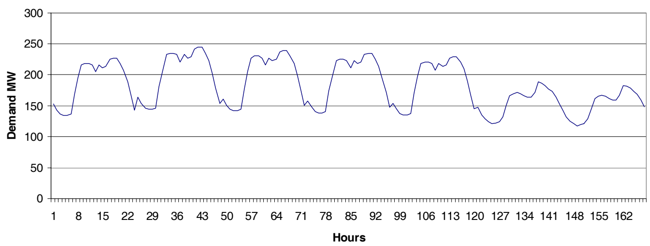

Fig 4. Demand variations during a week.

C. Responsive Demand

In our test system we have divided the loads into 3 categories; industrial, commercial and domestic. We assume that all responsive loads are available in domestic sector and will respond whenever output of windfarms drops. The response setting has defined as:

If Wind Output < 10MW then reduce the demand by 5%
If Wind Output < 5MW then reduce the demand by 10%

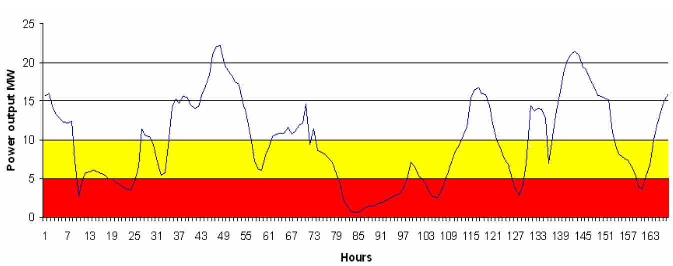

Fig 5. Aggregate output of Windfarms and effects level of responsive demand.

D. Variables

After scheduling the units to supply demand with zero percent penetration of wind power the results have been compared with 5%, 6% and 10% installed wind penetration connected to the network and by moving this amount of capacity across the network the benefit of locating then in each bus compared with other cases has been demonstrated. by dynamic optimization method, unit commitment (UC) has been performed [2]. The following variables have been considered and compared together in each case:

- total system emissions;
- system production costs;
- security violation index;
- value of wind.

V. Results

Generation Scheduling in presence of windfarm was performed and results shown below indicates the network variables which differ in each case.

A. Production Cost

Production cost which is assumed total running cost of conventional plants is shown in figure 6. Each unit has its own running cost and total cost is aggregation of them.
When we assume that loads in the network respond to wind variations, by shedding the demand according to our mentioned setting in III we see a big difference in production cost. This is not just because of supplying less demand; as each unit has different production cost and gas units which are usually being used to supply load for a short time are very expensive to run. When demand drops according to wind output reduction, the need for running gas units is minimized and as a result total production cost is lower.

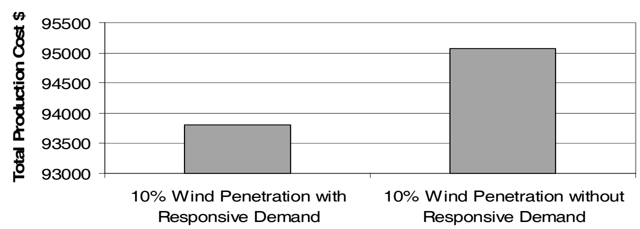

Fig 6. Total Production cost.

B. Total Emission:

Total emission in the network comes from conventional plants which spread NOx and CO2 into atmosphere. We have just considered NOx emissions in our study. Again by reducing the demand, need for running conventional plants at some points are eliminated and total emission is lower.

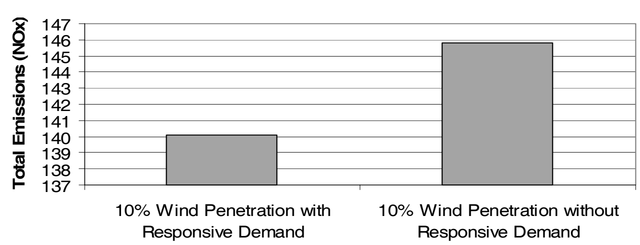

Fig 7. Total Emission.

C. Impact on Security:

Our main interest is impact of responsive demand on security index violation of network. Security objectives have been defined in II.8. One of the key issues in locating windfarms is network limitation in transferring power across the network on branches. This is one of our objectives which considers thermal limits of transmission lines. Another object is required amount of reactive power from generation units. Wind units can supply substantial amount of reactive power and by reducing the demand when windfarms have less energy share in the system, the need for getting more reactive power from other plants is eliminated and will result in more secure network. In terms of voltage limits in busbars, again by reducing the demand, those busbars which are accommodating conventional plants will not see much difference in output of conventional plants and voltage rise/fall does not happen.

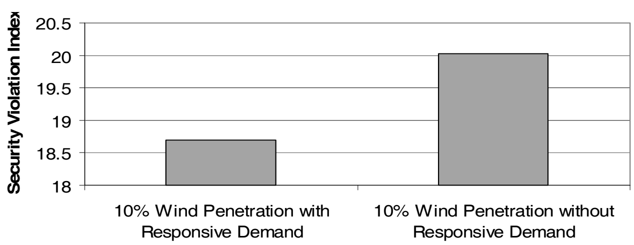

Fig 8. Security Violation Index

It must be noted that when security index is lower, it represents a more secure network as security objectives have less violation from their desired points; i.e. voltage in busbars can vary between 0.950-1.09 per unit. Below and beyond these points, unit commitment is invalid.

D. Impact on Value of Wind:

Value of wind is defined in equation below:

$$Value\ \ of\ \ Wind\ = \frac{C(No\ \ wind\ ) - C(\ with\ \ wind\ )}{P(Wind\ )}\ \$/_{MW} \qquad (12)$$

Where C is total production cost and P represents the installed wind capacity in MW.

Value of wind shows how much money could be saved through in supplying the demand per MW installed wind capacity. It is clear that by reducing the total generation cost (while we assume that we utilize total output of windfarms) value of wind increases by 17% in presence of responsive demand. This value could be vary by changing the methodology of implementing responsive demand and consider

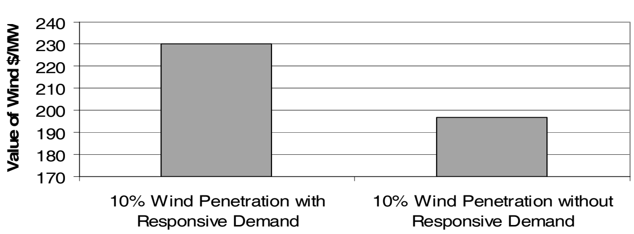

Fig 9. Value of Wind

VI. Conclusions

Responsive demand in networks with high penetration of intermittent generation can have a positive effect on operational, planning and environmental characteristics. It provides the opportunity for load growth and enhanced robustness with minimal addition growth of the transmission system, make greater use of renewable such as wind systems, increases energy efficiency and reduce pollution and emissions and increases the level of local reliability to ensure the necessary power quality standards has met.

In this project we assumed that in domestic sector we can have such responsive demand which responds to intermittent units output variations. Reducing the demand either automatically or by communication between network and load can benefit the network both in short term by improving the transmission capacity and will reduce the need for network reinforcement in long term. However if it requires communication between network and demand; then a substantial investment may be needed to provide such facilities.

In previous DSM methods shifting the demand has always been considered rather than shedding it. But it may not benefit systems with high penetration of renewables as much as networks with lower penetration as aim of shifting the demand is just to reduce the peak demand and reduce the need for running peaker power units. But this is not the only issue in networks with high penetration of renewables and a solution is needed to mitigate the output power fluctuations and this is the aim of responsive demand which considers shedding the demand.

Whenever shedding the demand is considered as a solution to improve the efficiency and reliability it must always be noted that evaluating the value of lost load (VOLL) is very important and not all types of loads are able to participate in responsive demand program.

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