OPTIMAL STRATEGIES OF VIRTUAL POWER PLANT DEVELOPMENTS : A REVIEW

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Abstract. *This paper reviews the fundamental concept of virtual power plant (VPP), its attributes and components as well, based on the related theories proposed by various researchers. Present power system constitutes numerous actors, in whole, in highly decentralized environments and liberalized electricity market. Within such conditions an optimized performance by VPP is expected. Hence an overview of different optimization approaches for virtual power plant is presented. A review was done on different schemes which monitor and control the dispersed distributed energy resource (DER) and loads integrated to VPP. The various mathematical formulations of bidding strategies for VPP, as given in different literatures, are discussed. The cyber security issues in VPP and mitigation strategies are also investigated.*

Keywords

Distributed energy resources, optimization, bidding strategy , cyber security

1. Introduction

There is a gradual development of centralized power generation to the distributed energy resources (DER) integrated into the existing legacy system at the distribution network level. Penetration of DER into the entire power system facilitates the liberalization of electricity markets, availability of standby capacity for peak demand, enhancement in reliability and power quality, augmentation of local electricity network, support to the existing grid, combined generation of electricity and heat, efficient use of low priced fuel, etc. [1-4], [6], [14], [27], [62], [67]. Now one question that arises, "what should be the business and technology platforms which are able to manage the variability of a generation of DER, diversity and complexity in the transfer of electricity to end users? " [32]. New technologies, which are also to be developed, should have capabilities to interface augmented power system infrastructure with power market stakeholders. System operators and other entities who deal with electricity markets should possess controllability and visibility of different DER and also there should be a requisite interfacing between these system components in order to achieve optimized monitoring and control operations [3], [34], [31], [64]. New acceptable business models need to be created along with expansion in power system elements because trading entities as per the repercussion of the enhancement in investment in DER, wholesale electricity market, demand response programs, energy storages, plug-in-electric vehicles (PEVs) technologies. Consumers are gaining prime importance in whole power system developments due to following objectives :a) to estimate and predict the proportion of customer participation in demand reduction b) to identify the localized demand response and its impact on a utilities' distribution system c) to include the demand response and distributed energy resources into utilities' action plan d) to identify the effect of reduction of load on the utilities' procurement plan [67].

There must be some ways to utilize demand reduction by consumers during peak and non-peak hours. The possibilities are to be examined such that, at the local level not affecting the power grid, a DER and a combination of DER can have generation capacity to cater the consumers' demand, at most, during peak hours and also to identify whether the production capacity of DER is surplus during peak hours as well as non-peak hours [48]. It is a challenging task to sum up the surplus power generation of different DER possessing the stochastic generation capacity. Whether, and also by which ways, it is possible to utilize the aggregated power available from dispersedly interconnected DER and demand reduction of numerous heterogeneous loads and then postpone new power system infrastructure developments with uprise of the power demand [32]. The aggregated power from DERs should be available for sale in electricity markets with a multitude of bids/offers [9], [14], [31], [37], [40], [42].

The concept of VPP is evolved to face and provide one possible solution to the aforementioned challenges. Although there is no unique definition of virtual power plant available, some experts tried to define VPP as given below. The VPP has been stated in following ways [32], [67]. “Virtual power plants essentially represent an ‘Internet of Energy’, tapping existing grid networks to tailor electricity supply and demand services for a customer,” and “They maximize value for both the end user and distribution utility, primarily through software innovations.” “How does a utility manage the complexities concerning the rollout of pricing, demand response and distributed energy resources for load reduction, ISO/wholesale market participation and/or distribution management? One way is through the use of Virtual Power Plants (VPPs).”

Efforts are needed to shape the VPP concept from its present hypothetical stage into a real time system [43]. Broadly speaking the VPP is based on actions such as aggregation, optimization and then dispatching [16], [32], [66]. In VPP, several power plants are confined into different clusters which are centrally managed [27]. The main feature of VPP is its ability to optimize the whole system while not looking for additional infrastructure developments [20], [32], [39], [61]. Some countries have significant limitations on infrastructure development so they are looking towards new models like VPPs. A mathematical model is developed in [67] for the VPP’s energy bidding scheme which can participate in regular electricity market and the intraday demand response exchange (DRX) market. An optimal offering strategy of a VPP in day ahead (DA) market is considered by proposing a stochastic adaptive robust optimization strategy [70]. The participation of VPP in the energy market is to be evaluated. To evaluate the performance of VPP under battery initial conditions, a methodology based on ‘cumulative performance index’ (CPI) is suggested [68]. The impacts of variations of energy storage devices’ rated capacities and charging/discharging periods on VPP performance are analyzed with adequacy assessment [71]. The short term spinning reserve risks of generating systems incorporating VPPs are discussed and evaluated in [72]. A binary backtracking search algorithm (BBSA) is proposed for 24 hours priority based optimal schedule of VPPs with and without microgrid [73]. For VPP, a bidding strategy optimization model which includes demand response and uncertainty of renewable generation is suggested in [74]. A bi-level optimization algorithm is proposed to achieve the optimal bidding strategy of VPP [75]. A fuzzy based optimization for bidding strategy is proposed in order to maximize the profit of VPP [76]. In transactive energy framework, to maximize the profits, the VPPs aim to schedule optimal hourly strategy in day ahead market. Next, VPPs try to minimize the imbalance cost in real time market [77].

In VPP, distributed control schemes are found better, compared to central control schemes, in solving economic dispatch problems because distributed control schemes are robust, easily scalable and possess lower cost of implementation [83]. Though, distributed control schemes show various advantages over the central control scheme, but these are prone to cyber-attacks. So, to mitigate the effects of cyber-attacks, an attack-robust distributed economic dispatch strategy is designed in [69].

The key objective of this paper is to explore the capability of VPP to integrate the resources in real time, and with high diversity and complexity, to control the load profiles of consumers, aggregate the generation profiles of resources and provide these profiles to traders involved in the electricity market. It is not mandatory for a virtual power plant that to have all of its components connected to the same physical network, although the components are coordinated by an appropriate networking infrastructure [34]. Virtual power plant operations are also to be evaluated based on commercial and technical parameters within different conditions and season [2], [3], [34].

The paper is structured in the following ways. Sections II and III cover the basic concepts of VPP and features which make it pragmatic to cater the challenges originated due to variability and diversity of DERs penetrated to the power system and deregulation of power system and electricity market. Section IV categorizes the comparison of micro grid and virtual power plant. Section V surveys the different approaches of VPP proposed by different researchers. Section VI discusses the different control strategies, such as direct control, hierarchical control, and distributed control, for VPP. As to apprehend the optimized performance of VPP, section VII analyses the different optimization approaches proposed by researchers. As the communication is the backbone of VPP, section VII investigates the communication infrastructure which may be appropriate for the VPP.

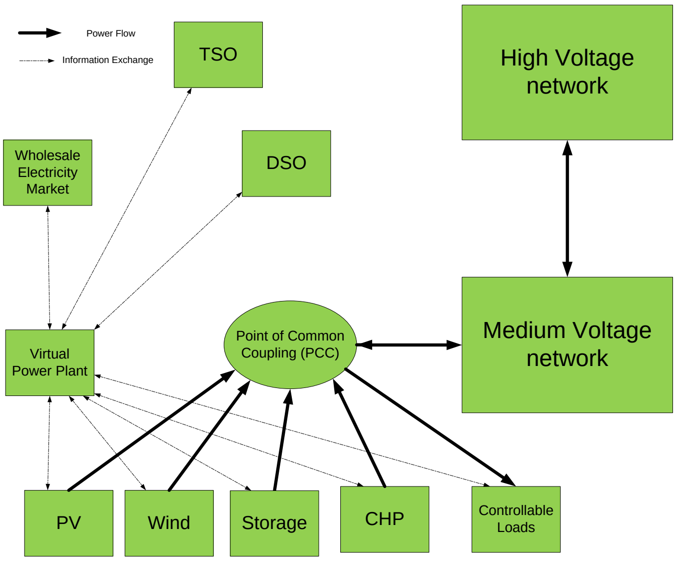

Fig. 1: Basic Architecture of Virtual Power Plant

2. Virtual Power Plant

A VPP represents the transformation of a whole power system which is highly distributed and scattered, and very complex in its operation, into a simple small power system that is intended to interact with other distribution utilities providing active power and some ancillary services. The basic concept behind a VPP is to aggregate the load of the customers (i.e. residential, commercial or industrial) [23] and massively interconnected DERs as well as conventional generators to aim for common pricing and demand response, single profile of electricity production. So all the actors involved in power system from electricity generation to the final end user consumption come under one umbrella with the particular program, as shown in Fig.1. The said concept of VPP allows to permit the utilities to aggregate all the concerned programs differed by types and locations in electrical networks. Estimation of the capacity of VPP can be done with the information accumulated in its database and reports gathered from different DER. The VPP is expected to ease the DERs to trade in wholesale energy markets (e.g. forward markets and the power exchange) and render a service in support of transmission system operator (TSO) for the management of various types of reserve, frequency and voltage regulation etc. In fact, VPP operates as a traditional power plant if viewed from the market. Internal structure of VPP tends to monitor and coordinates the individual resources of both generation and demand. VPP facilitates DER to exchange energy with high voltage grid and to participate in the electricity market as highlighted in the flow chart Fig.2.

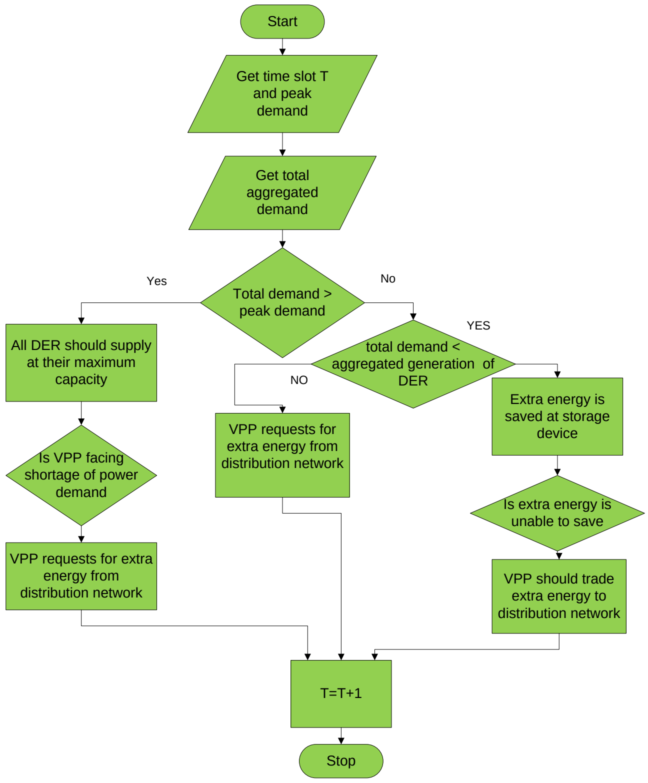

Fig. 2: Flow chart, how VPP deals with aggregated demand and aggregated generation

3. Attributes of Virtual Power Plant

3.1. Dispatch Scheduling

Various DERs technologies (i.e. solar and wind etc.) have to rely on unpredictable weather conditions so consequently their contributions to grid operation is limited and intermittent. Then, due to such imbalances created, DERs may be penalized with some economy. VPP paves the way via relevant ICT with requisite control schemes to transform non dispatchable state of DERs into the most economic dispatch scheduling condition on energy demand of consumers [35]. Remote dispatch commands can also be executed to any site which is a constituent part of VPP.

3.2. Local In Nature

The distinguishing quality of VPP as per technical is that it tries to accomplish the balance between production and consumption within the same low and medium voltage net so as to reduce the effect on high and extra high voltage networks. When power is delivered from remote generation to end users, the power loss is abated. This summarizes the local nature of VPP.

3.3. Segmentation

Geographically dispersed and functionally different customers and DERs are grouped to segment into some cells [35]. This grouping is done to achieve the enhanced and improved prediction and analysis based on the information gathered to the utility and existed database. In VPP, the entire electricity market can be subdivided in regional VPPs as shown in Fig.3. As VPP covers the highly decentralized environment, it is possible to segment the VPP based on the specific domain, such as DR-VPPs, mixed asset VPPs and whole-sale auction VPPs [67] Fig.4.

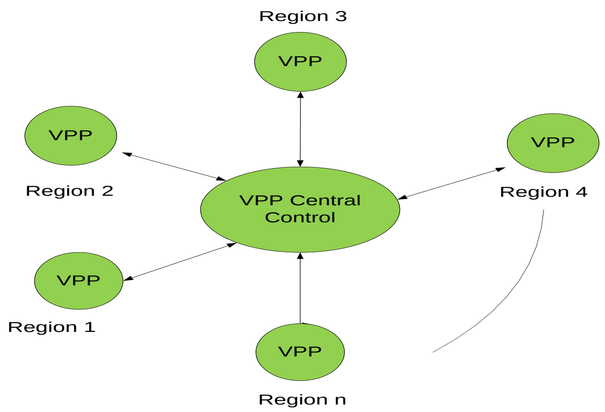

Fig. 3: Region wise segmentation of virtual power plant

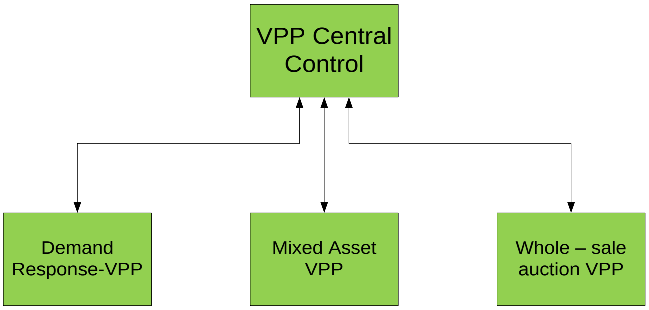

Fig. 4: *Domain specific segmentation of virtual power plant*

3.4. Coordination

To enhance the efficiency of overall VPP, it is needed the regulation of diverse elements of VPP (DER, consumers, market operators etc.) into an integrated and harmonious operation. A plan is to be devised to think about passive users, so that a load profile is shaped such that the balance of production and consumption is obtained with synchronization of operation of all elements.

3.5. Characterization

As already stated, in the VPP concept all the diverse elements such DER, controllable loads, system operator etc. are integrated into a single unit. Now, it is to be esteemed for representation of VPP in terms of some parameters. Authors of papers [2], [3] characterize VPP in terms of generator parameters (i.e. schedule of generation profile, generation limits, firm and maximum capacity, voltage regulation, standby capacity, active and reactive power capability, fault limits, fuel characterization etc.) and controllable loads properties (i.e. schedule or profile of load, rescheduling of maximum and minimum load, adjustment of load in market prices, capability of load to recover etc.).

4. Literature Survey Of Different VPP Approaches

4.1. Market based VPP (MBVPP)

The operation and action plans of MBVPP, an extension of VPP concept, are primarily based on and also focus to market signals. The MBVPP concept deals with the existing electricity market for trading the electricity within the MBVPP. The actions which are executed and the decisions which are implemented pertain to grid-oriented services and to regulate either forward markets or real-time markets. So, in other words the MBVPP facilitates to integrate DERs to the existing electricity market as well as the electrical grid via its internal market. Within the internal market, MBVPP behaves as a trader who bid for electricity and also it is sensitive to price signals. Inside the ambit of MBVPP actions, which are carried out, relate to the existing electricity market, internal market of MBVPP and business operators [4], [6], [14]. MBVPP avails two choices to aggregate, one is passive loads within its premises and another one is DER. In the latter case MBVPP acts as an energy supplier and can provide flexible generation portfolio so that it has the capability to trade both electrical energy and various ancillary services. The MBVPP basically behaves as a software based client server like EMS which controls and coordinates the overall system with requisite communication infrastructure. Different control schemes are proposed for MBVPP such as direct control, price signal control and internal exchange based on capability to handle different levels of complexity pertaining to decision makings [63]. The aforementioned control schemes are briefly described below :

4.1.1 Direct Controlled MBVPP

In this control scheme which is the highly centralized control scheme, direct access of DER is required. Complete knowledge of generation characteristics of DER and related information such as the location of DER etc. should be available to central controller. With an available generation portfolio, MBVPP can submit bids/offers to the electricity market such as day-ahead market [31]. After approval of submitted bids/offers, schedule of generation is to be allocated to each DER. In real-time, this is the highly cumbersome task to optimize the dispatch scheduling [63].

4.1.2 Price Signal Controlled MBVPP

In this control strategy, to regulate the generation schedule of DER, MBVPP communicates the information about price signal to DER. With hourly electricity price information available, energy can efficiently be utilized. With price information within the time slot such as five minutes available for the next time slot, MBVPP is able to achieve power balance in the system. Then, based on efficient price signal, aggregated generation/consumption profile of mixed generation portfolio is created and also the effects of varying price signal are also to be estimated. This control scheme faces a challenge of dealing with a lot of variables. Also illogical pragmatic human decisions taken at local level may create complexity in designing this control scheme [63].

4.1.3 Internal Exchange

This control strategy is highly decentralized in its functioning and performs less control action. Bids/offers are created and submitted by DER with the requisite information obtained from MBVPP which facilitates the internal exchange of electricity. These bids/offers are first cleared at the local level and aggregated bids/offer is submitted to the external electricity market for validation. With the approved bid/offer, generation/consumption schedules of the DER are made [31]. The schedule as said above is to be obeyed, in real-time, to avoid the possible penalty which may be imposed due to imbalances [63].

4.2. Commercial VPP(CVPP) and Technical VPP(TVPP)

Two types of VPP as commercial VPP (CVPP) and Technical VPP (TVPP) are proposed in [3], [6]. The description of CVPP and TVPP are based on market participation and system management and support. The acts of CVPPs pertain to commercial aggregation and ignore the network related operations such as stable operation of an active distribution network. TVPPs, on the other hand, include the DER scattered in the same location, and concern to the real time information monitored and obtained from local network integrated with DER. In response to above, output of TVPPs represents the cost and operating characteristics of aggregated DER [4]. Simply, CVPPs and TVPPs are described on the basis of 'commercial aggregation' and 'Network Service Aggregation', respectively [3], [6], [15], [16].

Thus, CVPPs facilitate the DER to participate actively in the electricity markets while minimizing the risk of system imbalance. The CVPP with appropriate optimization algorithm, while offering optimum level of energy to forward market, maximizes the objective: (expected profits) = (expected revenue from selling electricity) – (expected cost of not fulfilling the contract position) [3]. The aggregated CVPP profile does not include the effect of the distribution network. Any third party aggregator or a Balancing Responsible Part (BRP) can function as the operator of CVPP while accessing the market for energy etc. [4]. CVPP enables following services and functions [25].

1. Trading in the wholesale energy market
2. Balancing of trading portfolios
3. Submission of bids and offers to the system operator
4. Visibility and participation of DER units in energy markets
5. Maximization of value from DER participation units in the energy markets

The TVPPs facilitate the TSO to observe the operation of DER and to use the DER capacity. Hence, the total capacity of the entire local distribution network can be assessed. With the aforementioned information, aggregated grid profile can then be evaluated. Also with other bids and offers from all actors, real-time system balancing can be achieved [2], [3], [10]. Thus, TVPP enables visibility of DER units to the system operators, the contribution of DER units to the system management and optimal use of the capacity of DER units to provide ancillary services incorporating local network constraints [25]. The main functionalities as described in [15], [16] which are associated with TVPPs are as follows:

1. Continuous monitoring of the loading condition and retrieving with ease the retrospective data of equipment loadings
2. Self-identification/self-description of system components and their optimized management in support of available statistical data
3. Identification of fault location with automatic outage management and proper maintenance is to be facilitated
4. An overall optimized portfolio of DER is to be produced with statistical analysis of data

5. Control Schemes For Virtual Power Plant

The centralized, distributed and also hierarchical are the three primary schemes by which VPP can be controlled [5], [17]. In real-time via advanced metering infrastructure (AMI) VPP control center is able to monitor and control all the resources. Optimal integration of resources is possible by the VPP control center and an optimized aggregated profile of DER can then be evaluated. This profile can be produced for the wholesale electricity market, TSO and DSO. The VPP control center facilitates VPP to participate in the electricity market by preparing bids with the aggregated profile of resources as well as on demand and also optimize the overall operations [20], [33], [61]. Central decision making process of VPP control center creates the control actions as per the set points which are already defined to DER of VPP and deviations with the set points. The TVPP as proposed in [2], [3], [10] should have network control capability with knowledge of local network. Advantages and infrastructures related information is covered in [5], [17], [24].

5.1. Centralized Control

In the centralized control scheme, also known as direct control, all the entities are controlled via strong communication network by a central control unit of VPP. So all the DERs are accessed, and controlled directly by the VPP control center to meet the varying demands of the local power system, and the DERs respond to the control action received by them from the VPP control center [14], [17], [20], [22], [23]. Optimized operation of a VPP resource can then be obtained. In this control scheme all the action is performed at one common node and, thus, most of the information is collected at this point. Thus, implementation of suitable latest communication technologies may get impeded. Also, there is the possibility of failure to act of aggregation if the VPP control center loses its control of resources.

5.2. Hierarchical Control

In hierarchical architecture of control scheme, intermediate control units for aggregation are provided to aid the control action of a VPP control center. The raw information is not directly sent to the VPP control center, but the information is processed for aggregation at the intermediate level and then received by the VPP control center for making the aggregated profile, consequently slower responses are obtained in this control scheme [17].

5.3. Distributed Control

In this control scheme, the entire DER cannot be accessed directly by the VPP control center but are controlled by local controllers. In distributed control, system all entities of VPP possess the autonomy and the entities are free to determine their own optimal state within all existed constraints. In this scheme, resources can be allured to operate at desired condition and can be awarded the incentives. With this control scheme, the whole VPP can perform the aggregated operation in most adaptive ways with the presence of DER which produces fluctuating power. Local VPP aggregation function (LA) described in [17] represents and coordinates smaller geographical areas so that to lessen the data exchange at an intermediate level of aggregation.

In centralized and hierarchical control schemes it is possible to implement a common pricing policy for the resources depending on the type of the resources. But distributed control scheme facilitates the resources to choose the different pricing strategy for the generation and consumption and this pricing strategy can be altered accordingly during the occurrence of the contingency.

Tab. 1 A comparative study of control schemes

Sr. No.	Control Schemes	Merits	Demerits
1.	Direct Control	Whole aggregation is achieved at one node	Huge data exchange is done at one node
		Central Control centre has direct access of resources and delivery of information to resources is fast	Failure of Central Control Centre may hamper the aggregation process
2.	Hierarchical Control /Distributed control	Aggregated profiles are communicated to Central Control Center not raw data with information gathered at local level	Response to central control centre is slower as computation work is done at local and intermediate levels

6. VPP Optimization

With regards to the optimal operation of VPP, most of the authors have given thrust either in maximizing the profit of associated utilities, or minimizing the production cost and the cost that may incur in the transfer of energy to the end users [7], [8], [20], [23], [35], [31], [61], [68]. Some of the VPP optimization approaches are highlighted as below.

6.1. VPP Optimization Based On CPP

The proposed VPP consists of three power plants as wind power plant (WPP), PV and a gas turbine conventional power plant (CPP). A VPP optimization problem is formulated as described below while the objective is the minimization of operating cost of CPP . A case study is analyzed in research paper [13] .This case study is reckoned with a VPP consisting of a WPP with installed capacity of 9.6MW, PV with installed capacity of 6 MW and gas turbine with maximal power output of 5.67MW. The study is designed to consider the effect of the CPP technical minimum value on overall VPP costs. The study was lacking to develop a framework for inclusion of market prices, energy storage system as well as uncertainty modeling. A mathematical formulation of VPP optimization based on minimizing the operation cost of CPP is given below:

Notations

S_{conv} Start up cost of CPP

C_{conv} Cost of electricity production from CPP in period t (Rs/MWh)

$\mathrm{Y}_{\mathrm{conv}}(\mathrm{t})$ Binary variable equal to 1 if CPP is started at the beginning of the period and 0 otherwise

6.1.1 Formulation of VPP optimization

Minimize

$$\sum_{\mathrm{t}=1}^{T}\left(C_{\mathrm{conv}}(\mathrm{t}) + Y_{\mathrm{conv}}(\mathrm{t}).S_{\mathrm{conv}} \right) \tag{1}$$

The aforementioned VPP optimization problem is constrained to: output of CPP is equal to the summation of all possible production levels; setting the production price of CPP by time periods, bounds for each production level, maximal hourly RES electricity production and hourly ramp limits of CPP; ensuring the delivery of electricity in each hour.

6.2. Optimization With Direct Load Control

The direct load control algorithm is developed in [43] for the management of VPP while identifying the type, number and load reduction capabilities of integrated and sporadic controllable loads. Optimization method is discussed to aim to maximize the load reduction over the specified control interval with application of appropriate optimal control strategies to the controllable load. Consequently, a final minimum aggregated demand over a control period is obtained. This single profile representing the VPP can be offered by VPP in the electricity market by offering load reduction bids to the system operator. The proposed direct load control algorithm, input parameters and decision variables are described as follows.

As implementation of direct load control approach is based on the central controller, which collects information from the loads at remote locations, so a lot of data exchange is done by communication network which is not preferable. Also, consideration of non-controllable load is missing, the impact of non-controllable load is also to be regarded. The invisibility of the loads may hamper the viability of direct load control approach.

Notations

$\mathrm{z_i}, \mathrm{z_f}$	Initial, final time step of the control
$\Delta \mathrm{z}$	Time step duration
$forecLoad_{\mathrm{z}}$	Forecast load demand of the aggregator at time step z
$e_{\mathrm{kst}}(z)$	Variation in load consumption to devices of type k customer at time step z ,on application of control strategy(possible control action) s at time step t.
$Y_{\mathrm{kst}}(z)$	Number of devices of type k customer which are controlled on application of optimal control action s at time step t.

6.2.1 Formulation of DLC algorithm

$$\text{Min} \sum_{\mathrm{z=z_i}}^{\mathrm{z_f}} \left[forecLoad_{\mathrm{z}} + \sum_{\mathrm{l=1}}^{k} \sum_{\mathrm{n=1}}^{\mathrm{n_z}} \mathrm{Y_{ksz}}\, e_{\mathrm{ksz}}(z) + \sum_{\mathrm{l=1}}^{k} \sum_{\mathrm{t=z_i}}^{\mathrm{z-\Delta z}} \sum_{\mathrm{n=1}}^{\mathrm{n_t}} \mathrm{Y_{kst}}\, e_{\mathrm{kst}}(z) \right] \tag{2}$$

The followings are the major constraints which are subjected to the said DLC algorithm:

- For each customer type, the total number of connected devices of each customer type must be equal to the sum of the number of devices which are controlled and number of devices which are not controlled ,
- After the control period, demand must be less than a specified maximum limit which is although optional and is decided by aggregator to keep the generated payback within acceptable limits.

6.3. Dynamic Economic Approach

The algorithm for optimized control of VPP resources is proposed to be implemented via standardized communication technologies [30]. Economic dispatch condition can be obtained with communications integrated to optimize VPP control as all the DER controllers are equipped with IEC 61850 communications. With unified communications and economic dispatch scheduling, efforts are to be made to develop the model for VPP ancillary services. The proposed algorithm is shown below for determining the optimal active power production with IEC61850 endpoint setting for each DER.

In this algorithm, it is emphasized to include the effect of DER especially storage devices in the economic dispatch scheduling of VPP while ignoring the impact of conventional power plant and high voltage grid.

Notations

P_{ii}	Power output of the i^{th} generating unit at time t
p_i^{max}	Upper generation thresholds
p_i^{min}	Lower generation thresholds
$\alpha_{i,} \beta_{i,} \gamma_i$	cost coefficients of the ith unit $F_i = \alpha_{i,} \beta_{i,} \gamma_i$

P_{WTt} WT available production at time t

P_{PVt} PV available production at time t

P_{WTct} WT curtailment at time t

P_{PVct} PV curtailment at time t

inC_{PV} financial incentive for PV production per kWh

inC_{WT} Financial incentive for WT production per kWh

VPP_t VPP demand of electrical energy from the spot market at time t

ΔVPP_t VPP deviation from demand at time t

Δt sample time period

M number of generating units

N number of consecutively observed time intervals

ω linear penalty weighting factor for VPP power production deviation from the agreed value

6.3.2 Mathematical Definition

The objective function as shown below is composed of three components. The first component represents the minimization of fuel cost for conventional prime movers i.e. biogas and biomass, second part is to penalize the deviation of VPP production and the third one is to identify the violation done by fully controllable part of VPP on their commitment for pre specified production. However, second and third parts conflict with each other in their representation.

$$Min\Delta t \sum_{\mathrm{i}}^{M} \sum_{t=0:24/N}^{24} \left(\alpha_i P_{it}^2 + \beta_i P_{it} + \gamma_i \right) + \omega . abs(\Delta VPP_t) + (inC_{PV} P_{PVct} + inC_{WT} P_{WTct}) \quad (3)$$

Above mentioned objective function is subjected to constraints as there must be operating limits for CHP generators and storage devices, ramp limit of storage devices are to be defined, state of charge at the beginning and at the end should be same etc.[30].

6.4. Bidding Strategy Optimization With Uncertainty

With proper forecast methods of wind turbine and photovoltaic, the piecewise comprehensive cost model of VPP as cost minimization problem is shown below.The cost of renewable generation is assumed as linear function of its output.

$$\min_{P_j^{re}} C_{vpp}(k\Delta P) , \forall k = 1, \dots , N_{vpp} \quad (4)$$

s.t.

$$C_{vpp}(k\Delta P) = co_f^{wt} \hat{P}^{wt} + co_f^{pv} \hat{P}^{pv} + \sum_{j=1}^{N_{re}} C_j^{re}(P_j^{re}) \quad (5)$$

$$C_j^{re}\left(P_j^{re}\right) = a_j^{re} \, (P_j^{re})^2 + b_j^{re}\left(P_j^{re}\right) + c_j^{re} \quad (6)$$

$$\hat{P}^{wt} = \frac{1}{T} \sum_{t=1}^{T} P_t^{wt} \quad (7)$$

$$\hat{P}^{pv} = \frac{1}{T} \sum_{t=1}^{T} P_t^{pv} \quad (8)$$

10

$$(\widehat{k\Delta P)} = P^{wt} + \hat{P}^{pv} + \sum_{j=1}^{N_{re}} C_j^{re}(P_j^{re}) \geq N_{vpp}\,\Delta P \quad (9)$$

$$P_{j,min}^{re} \leq P_j^{re} \leq P_{j,max}^{re} \quad (10)$$

After solving the unit commitment problem, the piecewise bidding strategy with comprehensive cost set $\lambda_S^{vpp} = \left\{\lambda_1^{vpp}, \dots \lambda_k^{vpp}, \dots, \lambda_{N_{vpp}}^{vpp}\right\}$ is obtained . The bidding strategy is nondecreasing and comprises upper limit of price. The λ_k^{vpp} is defined as given below [74].

$$\lambda_k^{vpp} = C_{vpp}(k\Delta P) - C_{vpp}((k-1)\Delta P) + \delta C_{vpp}(k\Delta P) \quad (12)$$

$$\lambda_{k-1}^{vpp} \leq \lambda_k^{vpp} \leq \lambda_{k+1}^{vpp} \quad (13)$$

$$\lambda_{dn}^{vpp} \leq \lambda_k^{vpp} - \lambda_{k-1}^{vpp} \leq \lambda_{up}^{vpp} \quad (14)$$

$$\lambda_k^{vpp} \leq \lambda_{max} \quad (15)$$

$$\delta C_{vpp}(k\Delta P) \geq 0 \quad (16)$$

6.5. Stochastic Robust Adaptive Optimization

A virtual power plant is assumed to possess a conventional power plant, a wind-power generation, battery energy storage system and flexible loads. The stochastic robust adaptive optimal strategy of VPP for its participation in day ahead market is designed. The strategy is able to compensate the power deviations in real time market. This strategy is shown in following model which uses mixed integer linear programming (MILP) :

$$\max_{\emptyset_1} \min_{\emptyset_2} \max_{\emptyset_3} Pr_s \sum_t \left(\lambda_{t,s}^{da} P_{t,s}^{da} \tau + (\lambda_{t,s}^{rt} + \epsilon_{t,s}) P_{t,s}^{rt} \tau - CP_{t,s}\right) \quad (17)$$

s.t.

$$P_{min}^{da} \leq P_{t,s}^{da} \leq P_{max}^{da} \quad \forall t,s \quad (18)$$

$$P_{min}^{rt} \leq P_{t,s}^{rt} \leq P_{max}^{rt} \quad \forall t,s \quad (19)$$

$$CP_{t,s} = co_f a_{t,s} + co_v P_{t,s}^C + St_{up} b_{t,s} \quad \forall t,s \quad (20)$$

$$ES_{t,s} = ES_{t-1,s} + P_{t,s}^{ch} \eta_c \tau - P_{t,s}^{dis} \tau, \quad \forall t,s \quad (21)$$

$$P_{t,s}^{da} + P_{t,s}^{rt} = P_{WTt,s} + P_{t,s}^C + P_{t,s}^{dis} \eta_{dis} - P_{t,s}^{dem} - P_{t,s}^{ch}, \quad \forall t,s \quad (22)$$

where CP_t is the total production cost of CPP, $a_t = 1$ if CPP is producing electricity else $a_t = 0$, $a_t - a_{t-1} \leq b_t$ which is equal to 1 if CPP is started up otherwise 0, co_f is the fixed cost and co_v is the variable cost of CPP, ES_t is the energy stored in storage unit, P_t^C is power production of CPP, St_{up} is the start up cost of CPP, P_t^{dem} power demand consumption, P_t^{da} is the power sold/purchased in day ahead market, P_t^{rt} is the power sold/purchased in real time market, P_t^{ch} is the charging power and P_t^{dis} is the discharging power of storage unit, Pr_s is the probality of sth scenario, $\emptyset_1 = \{P_{t,s}^{da}, a_t\}, \emptyset_2 = \{P_{WTt,s}\}, \emptyset_3 = \{P_{t,s}^{rt}, CP_{t,s}, ES_{t,s}, P_{t,s}^C, P_{t,s}^{dem}\} \ \forall t,s$ [70].

6.6. Distributed Economic Dispatch Under Cyber Attack

A virtual power plant is assumed to comprise several sporadic distributed generators (DGs). These DGs are aggregated to obtain optimal power dispatch with their equal incremental costs. In distributed economic dispatch, total cost of generation of VPP is minimized with matching of active power to predecided demand. The aggregated optimization of VPP is shown below.

$$\min C_{total} = \sum_{i=1}^{N} C_i\,(P_{Gi}) \tag{23}$$

s.t

$$P_{out} = P_{ref} \tag{24}$$

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \tag{25}$$

where $P_{out} = P_{agg} - P^{dem}$, P_{agg} is the aggregated generation of VPP, P_{ref} is the reference dispatch decided by energy management system of the VPP. P_{Gi}^{min} and P_{Gi}^{max}
are minimum and maximum power output of DG i. The incremental cost of DG i can be calculated as shown below

$$\lambda_i = \frac{dC_i(P_{Gi})}{dP_{Gi}} = 2\alpha_i P_{Gi} + \beta_i \tag{26}$$

The incremental cost is updated and as shown below.

$$\lambda_i(\mathrm{k}+1) = \sum_{i=1}^{N} a_{ij}\,\lambda_j(k) + \rho b(P_{ref} - P_{out})$$

where $\rho > 0$ is the convergence coefficient. The equation can be written in following matrix form

$$\bar{\lambda}(k+1) = A.\bar{\lambda}(k) + \rho B(P_{ref} - P_{out}) \tag{27}$$

where $\bar{\lambda} = [\lambda_1, \lambda_{fl}]^T$ and λ_1 is considered to be IC of the leader and $\lambda_{fl} = [\lambda_2, \dots, \lambda_n]^T$ be the ICs of the follower.

$$\begin{bmatrix} \lambda_1 \\ \lambda_{fl} \end{bmatrix} = \begin{bmatrix} 1 - \frac{\rho}{2\alpha_1} & -\frac{\rho a_{fl}}{2} \\ A_l & A_{fl} \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_{fl} \end{bmatrix} + \left[\rho \left(P_{ref} + P^{dem} + \frac{\bar{\beta}\bar{\alpha}^T}{2} \right) \quad 0_{1\times(n-1)} \right]^T \tag{28}$$

In networked system, cyber attack may occur due to loss of data confidentiality, real information is affected while it is being sent from one agent to another one, and this information is not received by authorized agent. The replay attacks, stealthy attacks and denial-of-service (DoS) are example of cyber attacks [69].

$$\begin{bmatrix} \lambda_1 \\ \lambda_O \\ \lambda_R \end{bmatrix} = \begin{bmatrix} 1 - \frac{\rho}{2\alpha_1} & -\frac{\rho a_o}{2} & -\frac{\rho a_r}{2} \\ 0_r & I_o & 0_{r\times(n-1-o)} \\ A_1 & A_O & A_R \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_m \\ \lambda_w \end{bmatrix} + \left[\rho \left(P_{ref} + P^{dem} + \frac{\bar{\beta}\bar{\alpha}^T}{2} \right) \quad 0_o \quad 0_{(n-1-o)} \right]^T \tag{29}$$

Let in λ_{fl} the $\lambda_O = [\lambda_2, \dots \lambda_o]$ be the IC of wellbehaving DGs and $\lambda_R = [\lambda_{o+1}, \dots \lambda_r]$ be the IC of misbehaving DGs.The aforementioned dynamic economic dispatch converges to $[\lambda_1^*, \lambda_O^{*T}, \lambda_R^{*T}]^T$ which are obtained and as shown below,

$$(\lambda_1^* = \frac{1}{2\alpha_o}\left(P_{ref} + P_{load} + \frac{P_1}{2\alpha_1} - \frac{\alpha_o}{2} - \frac{\alpha_r}{2} \right)) \tag{30}$$

$$\lambda_O^{*T} = \lambda_o, \lambda_R^{*T} = (I_{n-1-r} - A_R)^{-1}[A_1\ A_O] \begin{bmatrix} \lambda_1^{*T} \\ \lambda_o^{*T} \end{bmatrix} \tag{31}$$

7. Requisite Communication Infrastructure

Unified communication technologies are inevitable now to facilitate the integration of multiple DER and software platform of VPP with a common communicative approach. Communication network is the backbone of

VPP, which is massively distributed and facilitates the VPP to achieve an optimal and adaptive control of the integrated resources. Different resources may be integrated to VPP via their own propriety communication protocols, and hence the costly and complicated protocol converter is needed to be developed [45]. The framework is to be developed in which different technologies and protocol are concurrent and all the prime features of legacy communication technologies should be included. In the conventional power transfer scheme, power flows to end users in simple one direction only while monitoring and controlling tasks are done by the SCADA system. Initially two protocols DNP3 and IEC 60870-5-101 were accepted for implementation by the increasing number of vendors for the accomplishment of tasks associated with substation SCADA systems [30]. The concept of VPP integrates conventional power plant and DERs at one node so power flows from DER also, which are located at end user sides. So, new operations and control challenges are emerging with these conditions. Thus, in VPP, implementation of ANM (active network management) system which is flexible enough to incorporate various technologies and protocols, and as well as does depend on customized solutions and/or proprietary communications protocols is explored [49]. The future ANM system adopted with standard data models of the IEC 61850 communication standard is proposed in [30] for VPP control with IEC 61850 information models and framework for creating IEC 61850 compliant software clients. The objective to implement unified communication architecture towards DER is realized while utilizing IEC communication standard. The IEC 61850 is mainly developed for substation automation by IEC working group TC57. IEC 61850 emphasizes both contents to be communicated and the process to communicate [48], [49], [51]. The IEC 61850 standard is extended with related development for wind power plant (IEC 61400-25), hydro electric power plants (IEC 61850-7-410), communication system for DER (IEC 61850-7-420), communication between substations (IEC 61850-90-1), communication between control centers and substation (IEC 61850-90-2), transmission of synchrophasor information according to IEEE C37.118 (IEC 61850-90-5) etc. As we know that scope of IEC 61850 is limited to substation automation [30], [49], [51], [59]. So efforts are to be made to extend the range of IEC 61850 to cover the network which integrates the whole VPP and also to coordinate with inclusion of common information model (CIM) which describes topological relationships between power system elements. Two other IEC standards as IEC 61970-301 which defines API for energy management system and IEC-61968-11 which covers system interfaces for distribution management may be tested for VPP network [53], [68]. The autonomous regional active network management system (AuRA-NMS) project implements the distributed and intelligent active network control strategies while improving the energy security and quality of supply [60]. The AuRA-NMS is based on the fundamental characteristics of agents in a multi agent system such as distributed in nature, autonomy, proactiveness, sociability etc. [50], [55]. The realization of AuRA-NMS in VPP distributed network control must also be studied.

7.1. MAS for VPP

As a virtual power plant is spread around in a decentralized system, multi-agent system facilitates VPP to take decisions at local level so that the main goal is achieved. The benefits of multi-agent technology for VPP are covered in [82]. It is stated that MAS solution, based on the distributed system, proves a better technology as it integrates more information as far as possible compared to solutions available for centralized systems. In an example, it is justified that parameters like actual maximum power or rate of production change of CHP units depend on the local temperature. In a centralized system aforementioned variables are considered constant in order to avoid complexity in the mathematical model. But in MAS solution more information about local temperature or estimation of heats can be incorporated. Also, with MAS technology excessive communication is avoided as a lot of information are shared among the agents so hence the effect of communication delays in the whole system is degraded. Reliability and robustness of the system can be achieved.

With MAS technology, multi-agents as local controllers can be provided to each entity of VPP. Dynamic set points are available to all the controllers to obtain the desired objectives at local level. In multi-agent system openness of the system is available as a programmable agent can be embedded in controller pertaining to DER units or loads. Thus, with ‘plug and play’ capability, more DER and loads can be added [81], [82].

8. Key Challenges For Virtual Power Plant

Fundamental concepts and some features of the virtual power plant have been thus far described. Now it is important to mention the functional challenges which are the repercussions of the penetration of DERs and consumers of different profiles in the electrical network. The challenges are included as follows.

- Via proper communication network, VPP is required to balance the two energy profiles (generation and loads). It is to identify that whether web based protocol such as TCP/IP and/or other communication standards such as IEC 61850 etc. is to be selected for implementation of the virtual power plant. If all components are connected via the internet for communication purpose, then the challenges of security and robustness of the system will be a matter of concern.

- Different new control system schemes with requisite infrastructures and computational software, also hybrid of these schemes, are to be developed and tested for implementation in highly decentralized power system for optimized operations of VPP. With such control schemes, it is expected to reduce exchange of the data and information to the high voltage grid.
- As the energy storage devices reduce the variability in the aggregated generation profiles of DER, it should be aimed to incorporate and integrate as much as possible the energy storage sources into the VPP. During an emergency, within very short time, these are able to maintain the status quo of the system.
- Some mechanisms are to be developed in order to reduce the effect of stochastic nature of DER, which are due to the dependency of DER operations on weather conditions.
- To predict and optimize the capacities of DERs while including both variable as well as fixed generation DER and then to make an aggregated profile require developments of new algorithms and mathematical models.
- A good metering infrastructure and appropriate computational software are to be realized in VPP so that DER can participate in power exchange trades, forward energy trades and energy balancing contracts. Thus, it is possible to reduce the power exchange with high voltage grid while making a reserve capacity of energy
- It is a cumbersome task to characterize the VPP in a uniform pattern as entities integrated into it, are of different domain areas and some of them have stochastic features. So management of virtual power plants is a multidimensional problem. The virtual power plant should provide a solution which can optimally balance all dimensions of the system.
- Till now the concept of VPP presented by the researchers integrates the resources, controllable loads, market operators, etc. But the impact of non- controllable loads so far is not studied. So a major challenge in the realization of VPP is the invisibility of loads and some DER interconnected in geographically different areas.
- In the highly competitive environment of electricity market some utilities may be specific in acquiring the power from the particular DER depending on their qualities of power generation. The virtual power plant must have improved control and management techniques to cater the aforementioned challenges. Also, the relationships among different utilities may create different type of challenge to the VPP.

9. Conclusions

This paper has presented a comprehensive study of available literature pertaining to the virtual power plant (VPP). It has been examined that virtual power plant will advance in two directions which are based on financial and technical aspects, although both are interdependent on each other. It has been investigated on which are the major entities involved in VPP. VPP receives data from different entities and computes the virtual power available for trading. A suitable control system with requisite communication technology is to be judged for such a computation purpose. Hence, different control schemes and communication infrastructure imperative to virtual power plant development have also been surveyed. Different optimization algorithms applied in bidding strategies, control application and mitigation of cyber attacks have been explored.

10. References

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