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Smart Virtual Power Plants for the Future Electric Grid – Realization and Benefits

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SUMMARY

A smart virtual power plant (VPP) concept is introduced in this paper, to form a major component of the future electric grid. The large scale integration of renewable energy and energy storage systems have introduced many technical and economic challenges to both customers and utilities. High levels of installed renewable capacity might reduce grid stability. Increased adoption of renewables and energy storage by customers on the distribution level might lead to high losses of revenue for the utilities. The VPP concept has the potential to resolve these issues and take on the roles of a major power station. The individual players in the VPP collectively work as one unit, which is ensured by smart control algorithms. The proposed VPP has two components: a forecast and analytics component, and an electrical systems control component. The forecaster generates the dispatch schedule for each player in the VPP and the loads. This is done by taking historical load and weather data, models of the VPP players, and the weather forecast as inputs. The electrical systems controllers use the dispatch schedule to regulate power flows from each individual player and to the loads. Grid frequency support and inertia emulation techniques are also discussed. An example VPP with solar photovoltaic and battery energy storage systems is presented and implemented using a real-time digital simulator. The results validate the VPP performance in load forecasting, power flow control and generator inertia emulation. With these performance improvements, individual small-scale power stations can collectively work as a virtual power plant, enabling them to participate in all kinds of energy markets and trading.

KEYWORDS

virtual power plant, grid resiliency, distributed energy resources, load forecasting, resource forecasting, generator emulation, droop control, voltage support, frequency support

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I. Introduction

The Traditional Utility Grid – 'Grid 1.0' and Challenges:

The electric grid as we know it, was designed for unidirectional power flow, with centralized power generation. The various players in the market had defined roles such as generation & transmission providers, utilities, customers, and regulators. However, in recent times, the boundaries delineating these roles have been blurred greatly. Power may now be generated, distributed and consumed in a multi-directional manner. There is an ever-evolving 'utility-prosumer' relationship. Increased distributed energy resource capacity has led to various technological and economic challenges.

Technological challenges: Increased distributed energy resources (DER) have the potential to affect service quality, grid stability and availability. There are also increased chances of voltage and frequency profile problems in the 'last-mile' grid. DER intermittency might lead to service interruption, which means system designers need to incorporate standby reserves (e.g. gas turbine generators) with high capital and operational costs [1].

Economic challenges: As the grid evolves, various economic challenges are faced by utilities and customers. DER capacity addition leads to loss of revenue for utilities while still having to maintain a fully rated grid. Utilities also have regulatory obligations to install energy storage systems for intermittency mitigation. In an extreme scenario, all residential customers could adopt rooftop PV and battery energy storage, leading to severe loss of revenue. This might in-turn lead to high rates for the end-users.

Social challenges: The deficiencies of the current utility grid have great impacts on society and quality of life. During natural disasters, grid resiliency is of paramount importance and the present grid has not always been successful. The centralized generation model has also contributed to pollution, high carbon emissions, fears about nuclear safety, etc. As more number of countries industrialize rapidly and become middle-income societies, tackling the technological, financial and economic, and social problems presented by the grid is no longer an option.

The aforementioned challenges open huge spaces for research, development and deployment of smart solutions for the future grid. One concept which has the potential to achieve all these objectives is the Virtual Power Plant (VPP). A VPP is truly an Internet-of-Things (IoT) which, through a mix of centralized and distributed controls, monitoring, diagnostics, prediction and forecasting could indeed form a major component of the future electric grid.

The Virtual Power Plant and its Advantages:

Virtual Power Plants are increasingly being identified as building blocks of the future electricity grid. Small generating stations powered by DERs, which may not be co-located, can together provide the same functionality as a large centralized megawatt-scale power station. This provides engineers, mathematicians and economists opportunities to reinvent the ways the utility grid operates – in terms of technology and economics.

Technological advantages: The role of utilities as mere energy providers may need to be re-evaluated in the VPP paradigm. In the future grid, utilities may play the role of localized energy dispatchers, processing power from central power stations, commercial solar PV and wind farms, residential power generators and energy storage. Real and reactive power injection capabilities lead to better load servicing and voltage profile management, reducing the stress on grid infrastructure and the need for expensive tap changers. With smart analytics and control, and installation of large scale energy storage, renewables intermittency problems may be mitigated. This provides capacity firming and without expensive upgrades. VPP also provides unparalleled telemetry access for the utilities to power flow through various feeders, load consumption profiles, bus voltage and phase angle profiles, and more accurate models of their service areas. It also provides remote capabilities to curtail or commit renewable sources and energy storage, smart grid enabled devices, and high power pulsed loads such as electric vehicle fast chargers.

Financial and economic advantages: Utilities need to maintain a reasonable revenue stream in order to continue operating as profitable and viable entities. But as discussed in the previous section, the proliferation of DERs could affect their ability to do just that. A VPP enables utilities to maintain economic competitiveness and financial well-being. Individual players in a VPP would pay a subscription fee in order to participate in the market. Residential and commercial consumers would continue to avail connectivity to the grid and uninterrupted service during DER non-availability. Thus the VPP can truly be a non-zero-sum game. Utilities may enter into power purchase agreements with customers, who are not bound by market expectations for profits and growth – hence agreements favorable to all participants may be achieved. Also with smart forecasting, VPPs are well placed to participate in short-term markets, increasing their revenue potential.

II. Proposed Virtual Power Plant Architecture

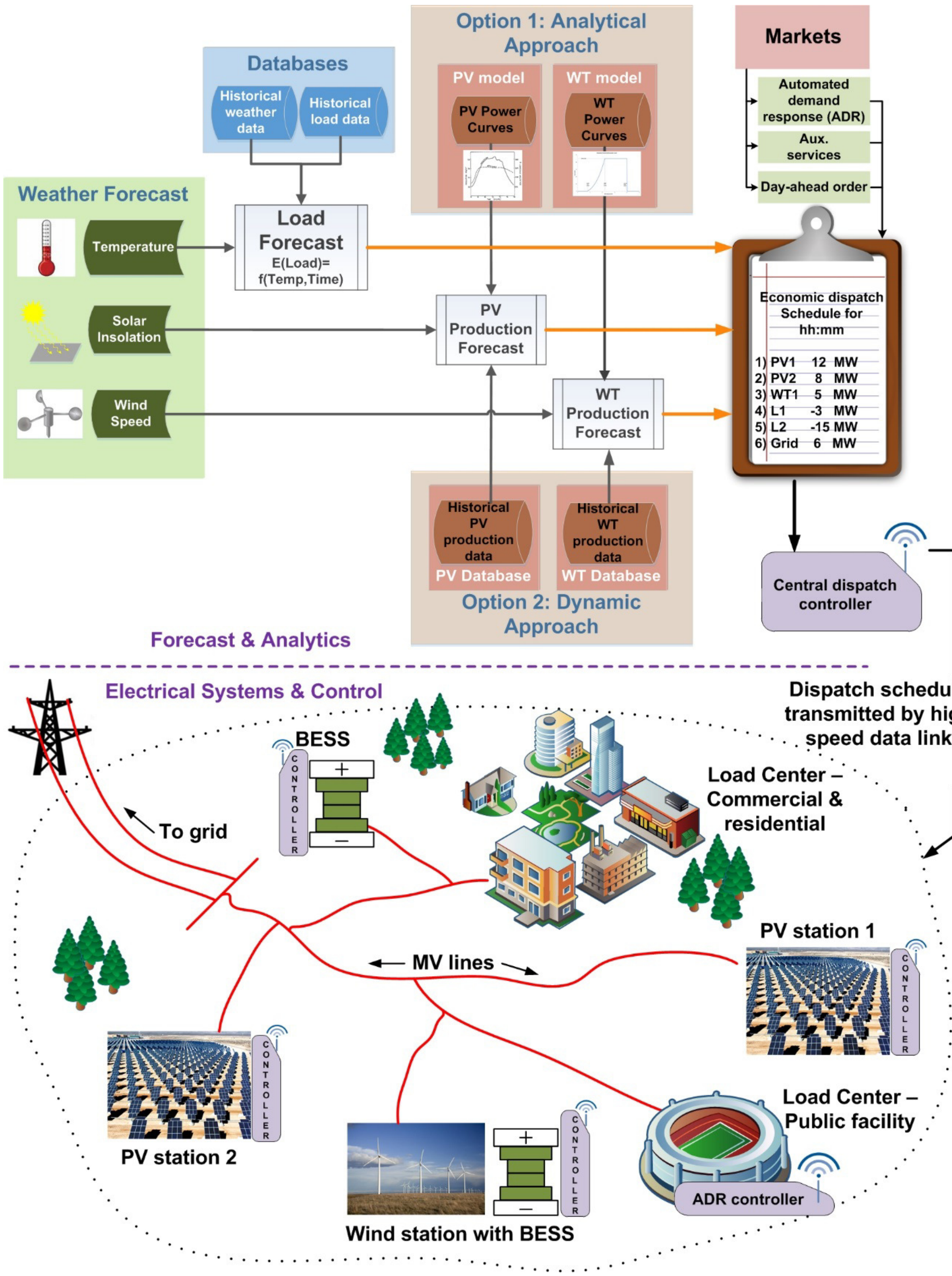

Fig. 1. Architecture and functional diagram of proposed Virtual Power Plant

The architecture of the proposed virtual power plant is shown in fig. 1. The system is envisioned to contain two distinct operational components: (1) a forecast and analysis component which produces the dispatch schedule for individual VPP players, based on load and resource availability forecasts, and market factors like pricing (2) an electrical systems and control component which processes power from the various VPP players, according to the dispatch schedule. The 'workflow' of a VPP may be best described using these two distinct operating regions.

(1) **Forecast and Analytics:** This supervisory function is part of the centralized dispatch controller of the VPP. It is assumed that accurate weather forecasts for the local area – air temperature, insolation, and wind speed – are available 24 hours in advance, for predefined time intervals. The controller has access to databases of historical weather and load data. Using regression analyses (described in the following section), the algorithm forecasts the local load in defined intervals. To perform resource forecasts, two methods may be employed: Option 1 is an analytical method, which uses precise models of DER plants in the VPP area and weather forecasts as input, and produces DER production forecasts. Option 2 is a system agnostic, dynamic approach, which uses historical DER production data and weather forecasts as inputs.

The economic dispatch schedule is then prepared using the load and resource forecasts, taking into consideration market inputs such as pricing, auxiliary service requirements, and automatic demand response. The dispatch schedule contains orders for various VPP players, including photovoltaic plants, wind power plants, demand response resources, and grid feed-in. The schedule is broadcast to the VPP players via a high speed communication network.

(2) **Electrical Systems and Control:** The forecast and analytics system described above is part of the supervisory controller of the VPP. The individual VPP players, such as PV and wind plants, battery energy systems, and demand response systems have their own second-level controllers, which regulate power flows from and into the respective systems. Upon receiving the generation and load schedule for the VPP dispatch, the controllers calibrate their respective real and reactive power references using droop characteristics. The local loads are serviced by the VPP and the excess power is delivered to the grid as per the dispatch schedule. In the case of VPP generation being less than the local load, the grid supplies the deficit. The control mechanisms for real and reactive power flows, grid support features, and generator emulation properties of the VPP are detailed in the following sections.

Overall, the sum total of individual players, their controllers, and the supervisory analytical and control algorithm can function as if they were one power plant integrated to the utility grid.

III. Load & Resource Forecasting

Forecasting is one of the fundamental components of the VPP's supervisory central controller. It makes power generation from the VPP dispatch-able with a considerable degree of accuracy. Forecasting has to be done both on the demand side and the production side, before they can be combined to calculate the VPP's net local load and net production. Fig. 1 focuses on four forecast algorithms:

- Local VPP generation forecasts:
  - Wind turbines generation forecast
  - Photovoltaic generation forecast
- Demand forecasts:
  - Local load profile
  - Grid feed-in profile

A. Load forecast:

Forecasting the load is a challenging process since it is not deterministic and cannot be calculated by analytical methods. Load forecasts are affected by stochastic fluctuations. But they can be estimated by analyzing patterns of historical data and their correlations. In this approach, a linear regression model which is based on the correlation between load, temperature and time is used to forecast load data for defined time intervals [2]. The regression model used is represented by the expression in (1).

$$E(load) = \left\{ \begin{array}{l} \beta_o + \beta_1 \cdot Trend + \beta_2 \cdot Day \cdot Hour + \beta_3 \cdot Month + \beta_4 \cdot Month \cdot T + \beta_5 \cdot Month \cdot T^2 \\ + \beta_6 \cdot Month \cdot T^3 + \beta_7 \cdot Hour \cdot T + \beta_8 \cdot Hour \cdot T^2 + \beta_9 \cdot Hour \cdot T^3 \end{array} \right\} \quad (1)$$

In the first step a set of training data (e.g. data from the past two years, time intervals one hour or less) is used to calculate the coefficients β_0 to β_9 in the linear regression equation in (1). *'Trend'* is a variable to capture the data trend over the whole span for which data is available; *'Day'*, *'month'* and *'hour'* are the times for which forecast is performed. In the training step the algorithm learns about the behavior of the load and identifies patterns based on date/time and temperature. The second step is forecasting the actual load of the system. The derived model equation (now with determined coefficients) and temperature from weather forecasts are used to predict the future load.

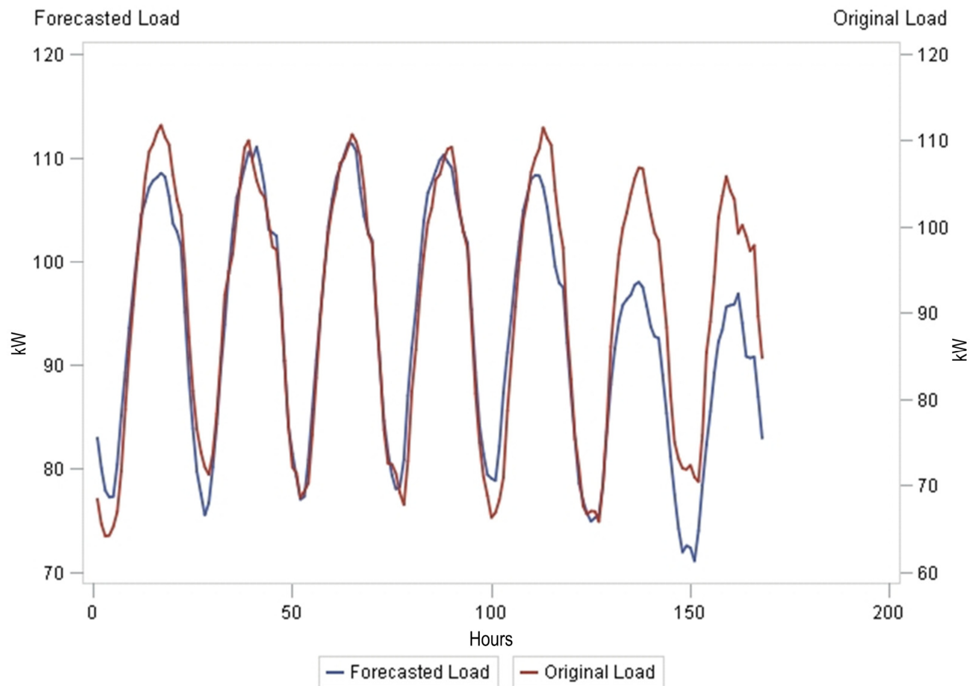

Fig. 2. Load forecast for one week performed using the described method Vs. the actual load demand for the same distribution area, as it happened later (Data collected from publicly available databases for a city in Pennsylvania [3]).

B. Resource forecast:

Resource forecast is defined as predicting the availability of real power from resources such as solar PV power plants, wind power systems, and other high dynamic systems such as demand response resources. Two methods may be employed, to perform resource forecasting of PV and wind power systems.

(1) **Analytical approach:** In this method the supervisory central controller has access to an up-to-date list of all power plants which participate in the VPP area, and each of their models and characteristic power generation curves (PGC). The wind speed and solar insolation forecast are then used to calculate the expected power output of wind turbines and solar PV plants. This method can provide a higher accuracy, but requires large amounts of data.

(2) **Dynamic approach:** This approach is more generic and system agnostic. The central controller does not have access to the list of wind and solar PV systems connected to the VPP, or their operating models. The second method is similar to load forecasting: a multiple linear regression may be performed using historical wind turbine and PV power production data, wind speed forecasts, solar insolation forecasts, and temperature. Since the controller is system agnostic, the system model which it uses is derived using measurement based techniques. The registration of

each new power plant to the central controller is not necessary since the controller learns the model with time. However the possibilities for inaccurate forecasts are higher since it always takes the algorithm a few time intervals and more measured data to adapt to the new generation characteristics.

IV. The Technology of Virtual Power Plants – Dispatch and Control

The overall control strategy of the VPP ensures its individual participants in aggregate emulate a standardized large-scale power plant. Not only is it supposed to meet active and reactive power demand, but should also provide dynamic characteristics that support frequency and voltage on various buses in the VPP network and the point-of-common coupling with the grid. To demonstrate the control and dispatch performance of the VPP, a basic example incorporating embedded distributed generators (DG), as shown in fig. 3, is used. It consists of a simple feeder, three PV power stations, two battery energy storage systems, an aggregated load and the grid itself.

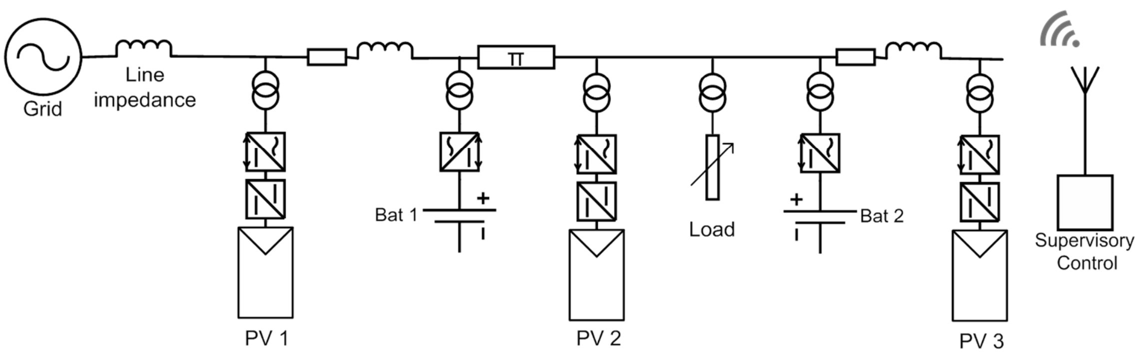

Fig 3. A demonstration example of a VPP, to be used in simulation

The control structure is multilayered, with the DG control being the bottom layer and the Dispatch and Command forming the top layer. The time scales tend to increase while the degree of autonomy tends to decrease as the hierarchy is traversed from bottom to top.

A. Distributed droop control

A key concept in VPP implementation is the emulation of output reactance (stator inertia) in those DG's which might not carry a hefty enough passive inductance [4]. This is achieved by programming the droop characteristics – which are inherently present in synchronous generators – into the inverter controls. Power flow from DG's to the grid is governed by (2) and (3).

$$P = \frac{V_{DG}V_{grid}}{X} sin(\delta) \approx \frac{V_{DG}V_{grid}}{X}\delta \tag{2}$$

$$Q = \frac{V_{grid}}{X}\left(V_{grid} - V_{DG}\cos(\delta)\right) \approx \frac{V_{grid}}{X}\left(V_{grid} - V_{DG}\right) \tag{3}$$

Active and reactive power flowing from each DG is governed by the power angle with respect to the grid (δ) and the reactance between these two voltage sources. The output voltage amplitude of each DG governs the flow of reactive power and provides a natural Volt/VAR droop (see (4)) that tends to support the voltage at the point of common coupling.

$$V - V_{ref} = -m_Q\left(Q - Q_{ref}\right) \tag{4}$$

Conventional real power control as utilized for synchronous generators is frequency droop, defined as follows:

$$\omega - \omega_{ref} = -m_p\left(P - P_{ref}\right) \tag{5}$$

In order to optimize the interaction of the components of the VPP, special Hz/W and V/VAR curves have been developed, as seen in fig. 4.

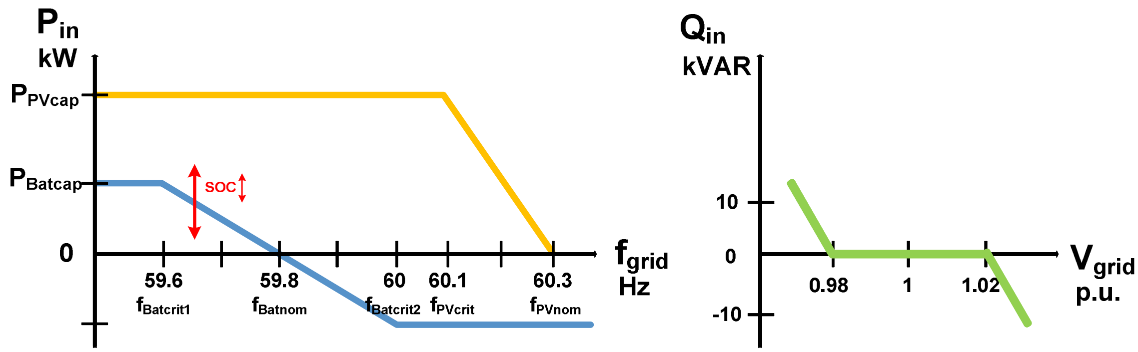

Fig 4. Hz/W and V/VAR droop curves implemented in the controller of the VPP

In the nominal frequency region of the grid (up to 60.1Hz), as seen in fig. 4, PV injects all available real power. If excess power on the network causes an over-frequency situation, the PV DG's curtail their power generation by following the droop curve to pull the network back towards the nominal frequency region. Simultaneously, the battery storage should behave as a load, abating linearly with the state of charge (SoC) according to the battery droop curve. This allows the charging to shed smoothly from the grid rather than abruptly. On the other hand, if the power in the system dwindles and the frequency is in the region $f_{battnom} < f < f_{battcrit2}$, the battery inverter droop curve should take effect with charging curtailed to reduce the load. If the frequency declines further ($f < f_{battnom}$), the battery inverter switches to discharging into the grid to support the frequency. Discharging is derated with SoC so that an abrupt shutdown of battery power is avoided.

B. Dispatch and command

On the top of the hierarchical control order is the central controller. Information from the resource forecasting and the load forecasting – obtained from methods described in the previous chapter – is fed to the central controller for the purpose of dispatching. The first priority of dispatch is to service the load. Additionally, the central controller is the interface for the energy market. As a result of the trading of the forecasted energy, the generation schedule for the VPP players will be prepared. This schedule is broadcasted to the individual VPP players. Based on the curves presented in fig. 4, the VPP participants' local controllers could determine in steady-state, the new PV and battery nominal frequencies, and consequently shift the curve to inject or to curtail power without hurting the frequency and voltage support characteristics.

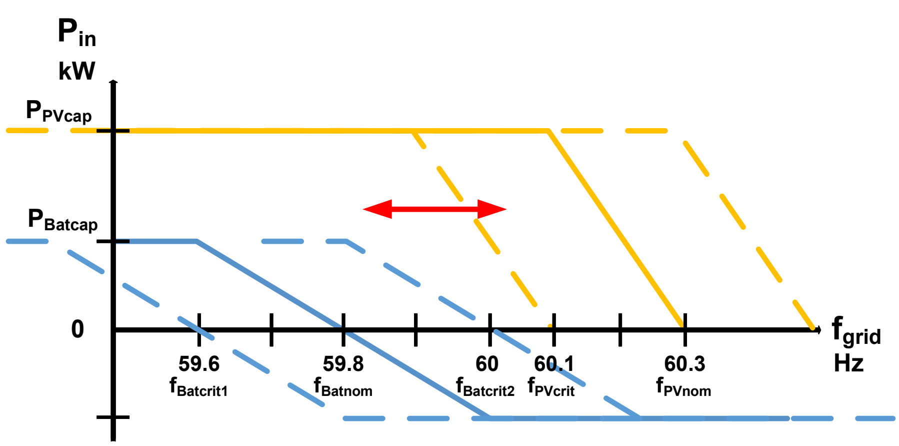

Fig 5. Hz/W curves are shifted based on input from supervisory central controller

C. Results from grid emulator

In order to demonstrate the operating principle of the central controller, a VPP model was constructed in the RSCAD environment in an RTDS system, with the architecture shown in fig. 3. Three time intervals from the dispatch schedule, as fed to the VPP players, are listed in table I. The forecasted load data is derived from the results discussed in fig. 2. The PV forecasting data are functions of PV system ratings; and the battery remains waiting in the network frequency support mode. As a result the traded real power is P_{sold}. Alternatively, to achieve the most profit on the energy market the schedule of the DGs could be optimized within certain boundaries. For instance, the battery could also operate in a profit mode without Hz/W curve, where it injects power for the highest possible revenues.

TABLE I. DISPATCH OF THE CENTRAL CONTROLLER

Time	11:00	12:00	13:00
$Load_{fore}$	106.60 kW	107.57 kW	108.76 kW
$PV1_{fore}$	63 kW	67 kW	70 kW
$PV2_{fore}$	55 kW	59 kW	62 kW
$PV3_{fore}$	57 kW	61 kW	64 kW
Bat1(SoC)	0 kW (SoC = 90%)	0 kW (SoC = 90%)	0 kW (SoC = 90%)
Bat2(SoC)	0 kW (SoC = 90%)	0 kW (SoC = 90%)	0 kW (SoC = 90%)
P_{sold}	68.4 kW	79.43 kW	87.24kW

The simulation environment is modified so that each time interval – lasting one hour – is represented by 20s of real time, in order to accelerate the simulation process. The performance of the VPP in regulating output powers from the DGs can be seen in fig. 6. Each hour the reference powers for each DG and the load change according to the dispatch schedule. Controller action regulates output powers within 5s. It is also noted that throughout this simulation example, the battery powers remain close to zero, since they are in network frequency support mode.

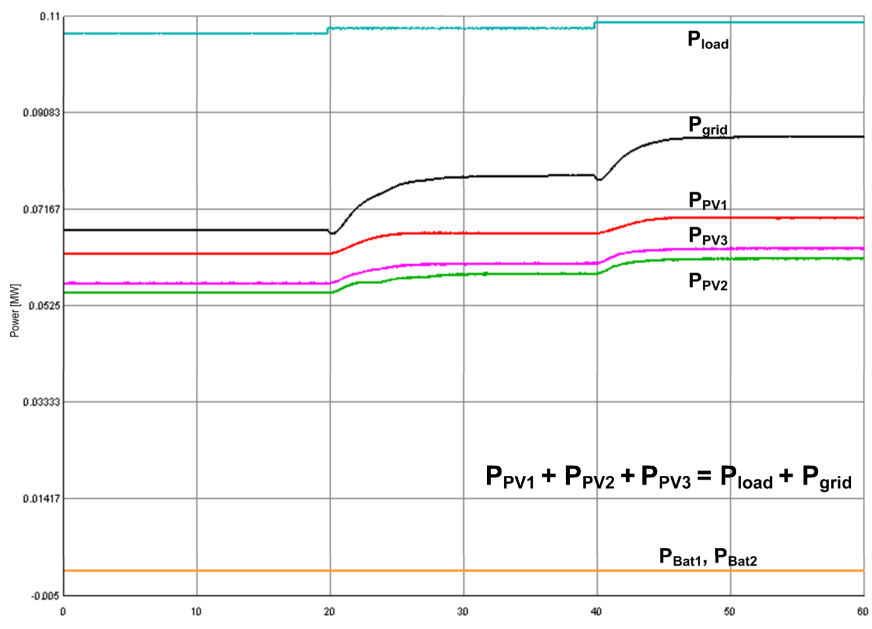

Fig. 6. Simulation of the three time windows from table I in RTDS, accelerated to 20 second periods

Another implemented feature is the emulation of synchronous generator output reactance (stator inertia) which kicks in when frequency transients occur. Fig. 7 shows the impact of a 100 kW pulse load on the bus, causing frequency transients. As a result, the PV generator connected to that node (or the closest neighboring node) delivers real power to provide frequency compensation. It is noted that the fluctuations in frequency are well within the grid tolerances.

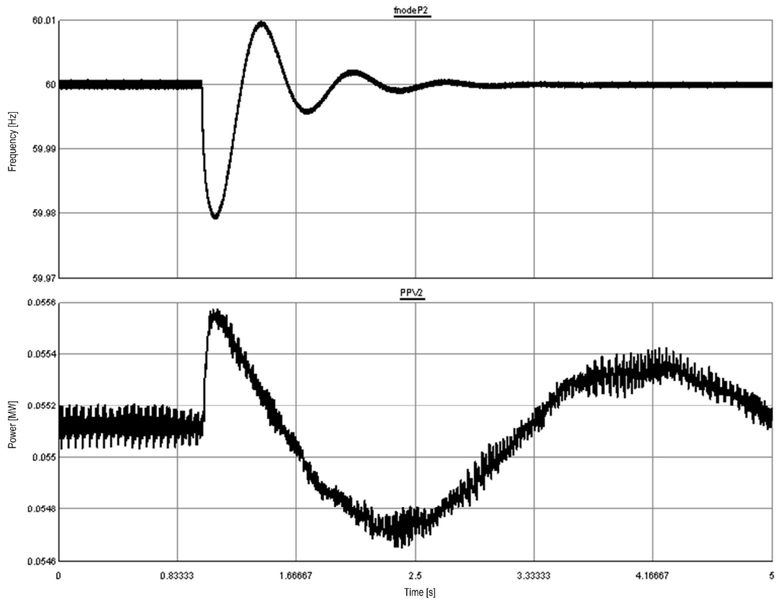

Fig. 7. Frequency transients after pulse load is introduced at a node and inertia emulation performance of the PV inverter

V. Conclusion and Future Work

The virtual power plant was introduced as an integral component of the future electric grid. VPPs have the potential to resolve many technological, economic and financial, and social problems which may arise due to inadequacies in the present grid. The proposed VPP solution has two components: a forecaster component and an electrical power systems component. The forecast solutions form the basis for dispatch schedules, which are broadcast to the VPP players. The local controllers, in turn, use the dispatch schedule to control and regulate power flow from the sources to the load and the grid, and also provide over- and under-frequency protection by droop control. Using real time grid simulators, the performance of VPP in forecasting and power flow control was verified. Local grid frequency support through machine inertia emulation was also demonstrated using RTDS emulation. Through these methods VPPs could assume the role of major generating stations in the future grid.

Many other challenges will have to be addressed in order to improve VPP performance and make the future grid smarter and more reliable. Realizing a truly system-agnostic VPP will be a major challenge. The ability to operate DGs in a plug-and-play manner without major improvements in communication infrastructure would have to be developed. This would also improve system reliability, since the VPP will be resilient to a communication link breakdown. Improvements to the control strategy are also needed to make the system immune to weather forecasting errors, by potentially introducing another control layer for the generators to operate under team-concept principles. Also, improving the time resolution of forecasting from the current one hour to 15 minutes or less will be another focus area in the future, thus advancing the level of VPP participation in the larger grid.

Acknowledgement

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