Virtual Power Plant Simulation and Control Scheme Design

CHEN ZHENWEI

Master's Degree Project
Stockholm, Sweden October 2012

XR-EE-ICS 2012:1513
Abstract.

Virtual Power Plant (VPP) is a concept that aggregate Distributed Energy Resources (DER) together, aims to overcome the capacity limits of single DER and the intermittent natural characteristics of renewable energy sources like wind and solar. The whole system can be viewed as a single large-capacity power plant from the system’s point of view.

In this project, the literature review of VPP concept, architecture, existed project and the survey of VPP in Sweden are being conducted first. Secondly, the simplified VPP model is built on MATLAB/Simulink software. The simplified system contains a wind farm, a hydro power plant, a dynamic system load and an infinite bus representing the large transmission grid. During the simulation process, the generation and consumption units are running according to the real history data located in external database. In the third place, optimized control schemes for the hydro unit in VPP model to decrease its effects on transmission grid are implemented in Simulink model. At the same time, hydro turbine should be controlled in an optimized way that without large turbulence. Basically, the hydro power plant is responsible for balancing the active power between the wind farm and dynamic load. Since there is a limit for the hydro turbine output, the rest of either power shortage or surplus power need to be compensated by the grid. This is the fundamental control scheme, so called run time control scheme. The advanced control schemes here are based on the moving average control method and forecast compensation control method. The forecast compensation control method use the 24 hours ahead load forecasting data generated by Artificial Neural Network. Later on, analysis of those three control schemes will be presented. The last part of the project is the conclusion of the different control schemes according to comparison of their control results.

Keywords.

Virtual Power plant, Distributed Energy Sources, Simulation, Moving Average, Load Forecast, Artificial Neural Network
Acknowledgements.

First of all, I would like to bring my sincere gratitude to my examiner at ICS department, Professor Lars Nordström, who clarified my thesis direction, gave me useful suggestions and brought me to related meetings that I had got lots of inspirations from.

For my supervisor WU Yiming, PhD student at ICS department, I want to say one thousands of thanks still far from enough to show my gratitude to your nice conducting job during my thesis project. You are so kind and patient that gave me comprehensive and detailed supports for my thesis.

Also I would like to thanks Post Doctor Arshad Saleem for sharing his experience on Virtual Power Plant and gave me those initial papers relevant to VPP.

To Nicholas Etherden from STRI, thank you so much for supplying the critical information in the simulation model.

For the PhD students Nicholas Honeth, ZHU Kun in ICS department, I would like to say thanks for your great supports at the beginning of my thesis. And also I would like to thanks Antonios Antonopoulos, PhD students in Power Electronics department, who gave me advices in modeling of battery. I want to thank Claes Sandels, PhD student in ICS department, who gave me the information in the Smart Grid Gotland project.

To my colleagues who also work on their master thesis in ICS department, GAO Shisong, ZHAO Pengcheng, Zeeshan Ali-Khurram, Davood Babazadeh, HAN Xue and the lab assistant Nils Edvinsson, thank you so much for your accompany in the lab that I had a such friendly and cozy environment to focus on my thesis job.

In the end, I am thankful for my dear parents, CHEN Yingqiang and ZENG Ailian, my sister CHEN Zhenjie and my lovely girlfriend Matilda Svärd. Thank for your mentally supports on my thesis work. Your supports and inspirations gave me the courage to overcome troubles and release pressure.
List of Figures

Figure 1 – Renewable generation in the electricity certificate system by hydro power, wind power and biomass power (excluding peat), 2003-2010. In TWh. [1]- 1.

Figure 2 – Share of renewable energy in Sweden, 1990-2009, in per cent.[1] - 2 -
Figure 3 – The architecture structure of VPP [1] - 5 -
Figure 4 – Structure diagram of EU-Eco Grid project[1] - 6 -
Figure 5 – Control Unit Functions of the Regenerative Combined Power Plant project - 8 -
Figure 6 – GUI in the control unit[1] - 8 -
Figure 7 – Gotland Smart Grid Project - 9 -
Figure 8 – Prototype of VPP model in simulation - 10 -
Figure 9 – VPP model in Simulink - 11 -
Figure 10 – Control Center block - 11 -
Figure 11 – Transmission Grid - 12 -
Figure 12 – Bus bar - 12 -
Figure 13 – Transmission line - 13 -
Figure 14 – Hydro power plant - 13 -
Figure 15 – Hydro power plant model inside the mask - 14 -
Figure 16 – Load - 15 -
Figure 17 – Dynamic system load model inside the mask - 16 -
Figure 18 – Wind farm - 16 -
Figure 19 – Measurements block - 17 -
Figure 20 – Measurement unit block inside the mask - 17 -
Figure 21 – Controller block - 18 -
Figure 22 – Run time control block - 18 -
Figure 23 – Moving average Controller block inside the mask - 19 -
Figure 24 – Moving average block - 19 -
Figure 25 – Forecast compensation control block - 20 -
Figure 26 – The ideal designed output of hydro power plant in 20th Dec, 2010 - 21 -
Figure 27 – Callback functions - 21 -
Figure 28 – Flow chart for data usage in simulation - 22 -
Figure 29 – Noise in the signal - 23 -
Figure 30 – Observed blocks in the simulation - 24 -
Figure 31 – Run time control illustration - 25 -
Figure 32 – The moving average window - 26 -
Figure 33 – Comparison of different moving average sizes[13] - 27 -
Figure 34 – Moving average control illustration - 27 -
Figure 35 – Forecast compensation control illustration - 28 -
Figure 36 – Artificial Neural Network structure ........................................... - 29 -
Figure 37 – Black box of the ANN structure ............................................ - 30 -
Figure 38 – Mathematical structure of ANN ............................................. - 30 -
Figure 39 – Dividing the sample data into two groups ............................. - 32 -
Figure 40 – Working flow of building ANN ............................................. - 33 -
Figure 41 – Data usage in different control schemes ............................... - 34 -
Figure 42 – Scatter diagram of temperature and load ............................ - 35 -
Figure 43 – Structure of input data for ANN .......................................... - 36 -
Figure 44 – Structure of output data for ANN ......................................... - 37 -
Figure 45 – Dividing the sample data to two groups for ANN ............... - 37 -
Figure 46 – Matlab Neural Network Fitting tool .................................... - 38 -
Figure 47 – Neural Network Training in MATLAB .................................. - 39 -
Figure 48 – Comparison diagram between forecasted load and real load... - 41 -
Figure 49 – Criteria for smoothly control exchange power in VPP .......... - 41 -
Figure 50 – Criteria for smoothly control output of hydro power plant...... - 42 -
Figure 51 – Results of run time and moving average ............................... - 43 -
Figure 52 – Results of run time and moving average (zoom in) ............... - 44 -
Figure 53 – Comparison of overall error and moving average size .......... - 45 -
Figure 54 – Results of only forecast control and the others control schemes - 46 -
Figure 55 – Results of only forecast control and the others control schemes (zoom in) ...................................................................................................... - 47 -
Figure 56 – Overall error in different moving average control schemes...... - 48 -
Figure 57 – Results of forecast compensation control and other control schemes - 49 -
Figure 58 – Results of forecast compensation control and other control schemes (zoom in) ...................................................................................................... - 50 -
Figure 59 – Overall errors of forecast compensation control with different compensate factor ................................................................. - 51 -
List of Tables

Table 1 – Service........................................................................................................... - 4 -
Table 2 – The detail information of EU-EcoGrid Project ............................................. - 6 -
Table 3 – Block Parameters: Transmission Grid......................................................... - 12 -
Table 4 – Block Parameters: Bus bar ........................................................................... - 13 -
Table 5 – Block Parameters: Transmission line ......................................................... - 13 -
Table 6 – Block Parameters: Synchronous Machine..................................................... - 14 -
Table 7 – Block Parameters: Excitation System ........................................................... - 15 -
Table 8 – Parameters of ANN for training ................................................................. - 39 -
Table 9 – Results from different structures of ANN for training ......................... - 40 -
Table 10 – Parameters of best structure of ANN .......................................................... - 40 -
Table 11 – Results from different control schemes ..................................................... - 44 -
Table 12 – Results of forecast compensate control ..................................................... - 47 -
Table 13 – Results of different moving average size .................................................... - 48 -
Table 14 – Results of forecast compensate schemes with different compensate factor.................................................................................................................. - 50 -
Table 15 – Which control method is the best............................................................... - 52 -
Abbreviation

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>VPP</td>
<td>Virtual Power Plant</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed Energy Resources</td>
</tr>
<tr>
<td>CDE</td>
<td>Controllable Distributed Energy</td>
</tr>
<tr>
<td>CVPP</td>
<td>Commercial Virtual Power Plant</td>
</tr>
<tr>
<td>TVPP</td>
<td>Technical Virtual Power Plant</td>
</tr>
<tr>
<td>DSO</td>
<td>Distribution System Operator</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>ICT</td>
<td>Information Communication Technology</td>
</tr>
<tr>
<td>IPO</td>
<td>Initial Public Offerings</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS

Abstract. ii  
Keywords. ii  
Acknowledgements. iii  
List of Figures iv  
List of Tables vi  
Abbreviation vii  
Table of Contents viii  
1 Introduction 1  
  1.1 Awareness of renewable energy and environment in Europe 1  
  1.2 Renewable Sources in Sweden 1  
  1.3 Research background on this paper 2  
2 Virtual Power Plant 3  
  2.1 Definition of VPP 3  
  2.2 Types of VPP 3  
  2.3 Services can be offered by VPP [] 3  
  2.4 Key units for VPP 4  
  2.5 An Example of VPP 5  
  2.6 Typical implementation of VPP 6  
3 Simulation of VPP 10  
  3.1 Prototype of simulation model 10  
  3.2 Simulation model in MATLAB 10  
  3.3 Data usage for simulation 20  
  3.4 Data exchange between the simulation model and external database 21  
4 Control of VPP 23  
  4.1 Backgrounds 23  
  4.2 Control Goals 24  
  4.3 Control schemes 24  
  4.4 Data usage in different controlling methods 34  
5 Results and Analyze 35  
  5.1 Forecasting results and analysis 35  
  5.2 Control results and analysis 41  
6 Conclusion 52  
7 Future work 53  
8 REFERENCES 54
CHAPTER 1 INTRODUCTION

1.1 Awareness of renewable energy and environment in Europe

Electricity comes from renewable energy should be take 20% in the total electricity producing in 2020, according to the so called ‘20/20/20’ targets establish at the spring summit in 2007 amount European Commission. As a member of European Commission, Sweden obligates to achieve the common goal among all EU members. Individually, the target for Sweden is to share 49% in total electricity production by 2020. [1]

For the greenhouse gas emissions, the EU has set up a similar goal as renewable energy, to reduce emission by 20% compared with the level in 1990. For Sweden, it’s a more ambitious goal, 40%. Also, Sweden will try to avoid net emissions of greenhouse gases into atmosphere in 2050. As parallel, the Swedish government has set up proposals to modify taxes and other economic policies to encourage stakeholders to achieve the ambitious goal. [1]

In 2003, Swedish government proposed Renewable Energy Certificates (REC) to promote the production from renewable energy sources. The generation unite can achieve 1 REC from producing 1 MWh electricity by renewable energy. All the electricity suppliers need to buy those certificates corresponding to a certain proportion of how much they sale and consume respectively. [2]

1.2 Renewable Sources in Sweden

In Sweden, the hydro power, nuclear power takes most of the percentage of power production. And the rest is wind power, biomass power, and waste power. The renewable energy has increased dramatically in the previous years. Here are some diagrams and table illustrates this point of view.[1]

The top fast growing renewable energies are biomass, wind power and waste power.
Since 2005, the increasing speed of renewable energy development dramatically increased to a highest level in history. Renewable energy came to 17.3 TWh in 2010. The biofuel energy production increased most fast, the wind power is the second, and then the hydro regarding the annual production. If consider the installed capacity, the wind power is the most fast growing one. There are just a few solar power plants in Sweden since the sunny days is rare especially during the 6 month winter. The supply of biofuels, peat and waste has doubled to 141TWh in 2010 compared with the production in 1983. [1]

1.3 Research background on this paper

As the society realize the renewable energy can bring benefits to our daily life and our vulnerable environment. How to use them in a smart and optimized way has attracted lots of scientist to research on it.

The Virtual Power Plant including small hydro, wind turbine, biomass and waste energy and other distributed energy resources. It supplies a new concept of address renewable energy generation that can overcome the natural intermittent characteristics of some renewable energy source like wind and solar.

This paper focus on simulation of Virtual Power Plant and design optimized control schemes. The simulation model is built in MATLAB/Simulink. The optimized control schemes are run time control, moving average control and forecast compensation control.

This thesis is conducted in Industrial information and Control System, supervised by PhD student, WU Yiming and Professor Lars Nordström. It officially starts from March of 2012 to October of 2012.
CHAPTER 2 VIRTUAL POWER PLANT

2 VIRTUAL POWER PLANT

2.1 Definition of VPP

There are lots of definition of VPP nowadays, but the most popular definition is defined by European project CRISP, “Virtual Power Plant is an aggregation of DER units disperse among the network but controllable as a whole generating system”.[3]

Also, there is another popular definition by European FENIX Project, “A Virtual Power Plant (VPP) aggregates the capacity of many diverse Distributed Energy Resources (DER). It creates a single operating profile from a composite of parameters characterizing each DER unit and can incorporate the impact of the network on aggregate DER output. A VPP is a flexible representation of a portfolio of DER that can be used to make contracts in the wholesale market and to offer services to the system operator”.[4]

In short, we can summarize the definition has two key points: “Firstly, different levels of aggregation are possible”, “secondly, dispersed CDE units are controllable by the VPP”(where ‘CDE’ is short for ‘Controllable Distributed Energy’) [5]

2.2 Types of VPP

There are two types of VPP. First, Commercial VPP (CVPP) and the second one is Technical VPP (TVPP).

Here are the definitions of those two types of VPP by FENIX project.

“A CVPP has an aggregated profile and output which represents the cost and operating characteristics for the DER portfolio. The impact of the distribution network is not considered in the aggregated CVPP profile. Services/functions from a VPP include trading in the wholesale energy market, balancing of trading portfolios and provision of services […] to the system operator. The operator of a CVPP can be any third party aggregator or a Balancing Responsible Party (BRP) with market access; e.g. an energy supplier.”

“The TVPP consists of DER from the same geographic location. The TVPP includes the real-time influence of the local network on DER aggregated profile as well as representing the cost and operating characteristics of the portfolio. Services and functions from a TVPP include local system management for DSO, as well as providing TSO system balancing and ancillary services. The operator of a TVPP requires detailed information on the local network; typically this will be the DSO.” [4]

2.3 Services can be offered by VPP [6]

1. Frequency control

Since the frequency related to both of the generation and consumption, and only the TSO can control both of those two parts at the same time, so TSO responsible for controlling the frequency. For example, the TSO can change the on-load tap changer to adjust the frequency.

2. Voltage control

Due to the factor that voltage highly relates to the reactive power situation, so TSO and DSO can adjust it separately. For example, TSO can put Static Synchronous Compensator (STATCOM) to adjust the voltage in the points of the transmission line. DSO can tune the reactive consumption by power electronics for controlling voltage.
3. Flow control
Voltage can affect the power flow in the transmission line, and the voltage control depends on both transmission system operator and distribution system operator. So obviously, the TSO and DSO in charge of control the flow.

4. Stability enhancement
The stability issues usually exist on the transmission line, the oscillation of frequency lead in stability problems. As a responsible unit for frequency control, the TSO also responsible for stability enhancement.

5. Security and reliability enhancement
Regarding the overall security and reliability, both of the TSO and DSO are responsible for the enhancement of security and reliability.

<table>
<thead>
<tr>
<th>Service</th>
<th>Responsible Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency control</td>
<td>X</td>
</tr>
<tr>
<td>Voltage control</td>
<td>X</td>
</tr>
<tr>
<td>Flow control</td>
<td>X</td>
</tr>
<tr>
<td>Stability enhancement</td>
<td>X</td>
</tr>
<tr>
<td>Security and reliability enhancement</td>
<td>X</td>
</tr>
</tbody>
</table>

2.4 Key units for VPP

Generation units
- CHP (Combined Heat and Power)
- Biomass and biogas
- Small power plants (gas turbines, diesels, etc.)
- Small Hydro-plants
- Wind based energy generation
- Solar production
- Flexible consumption (controllable/dispatchable loads)

Energy Storage units
- hydraulic Pumped Energy Storage (HPES)
- compressed air energy storage (CAES)
- flywheel energy storage (FWES)
- super conductor magnetic energy storage (SMES)
- battery energy storage system (BESS)
- supercapacitor energy storage (SCES)
- hydrogen along with fuel cell (FC)
Information Communication Technology units (ICT)

- Energy Management Systems (EMS)
- Supervisory Control and Data Acquisition (SCADA)
- Distribution Dispatching Center (DCC) [7]

2.5 An Example of VPP

As the figure 3 shows, the example of VPP contains those units:

- Generation units: a solar power plant, a wind power plant, a combined heat and power unite.
- Energy Storage units: Battery Bank
- Consumption unit: Household load

All those units are connected with a transformer. Also those units are connected with the control center which can send and receive the measurement information and command information amount those units.

The renewable energy has the higher priority to generate power, when there is a surplus generation, the surplus power can be stored in the battery bank. When the renewable energy cannot supply enough power to the load, the storage unit and conventional power plant will put in operation to compensate power shortage.

Obviously, the Information Communication Technology tool plays a critical role here to control the VPP. It works as the sensor and hands for the control center of VPP, the brain of VPP. The ICT responsible for observing the system by measuring the power flow, voltage and frequency, making decisions to adjusting the active power and reactive power generation, charging or discharging the storage unit and keeping balance of the VPP system.

The optimized control scheme is one of the most important parts in the control center. All the control commands rely on this scheme arranging the generation units and storage unites to optimize profit while achieving control stability.

Those generation units and energy storage system had been developed for quite a long time. Renewable energy source like wind farm and solar farm have been built all around the world. However, the Virtual Power Plant is just a new concept that far young behind the generation and storage technology. So now most of the challenge for the
VPP is how to aggregate the existed units together and control them in an optimized way by Information Communication Technology.

2.6 Typical implementation of VPP

**FENIX**

The typical research of VPP in Europe is the Flexible Electricity Network to Integrate the eXpected energy evolution’ (FENIX), leading by some of the Research Centres, Universities, Transmission and Distribution Utilities, equipment and ICT manufacturers, DER owners, and organizations responsible for regulation, standardization, etc. in UK, France, Germany, Netherlands, Romania, Spain, Austria. It began in 2004 and ended in 2009.

Their object is: “To boost DER (Distributed Energy Resources) by maximizing their contribution to the electric power system, through aggregation into Large Scale Virtual Power Plants (LSVPP) and decentralized management.”

The project has achieved those successes, as mentioned in the report: “During the demonstration we were able to monitor the simulated power output of DERs individually within SCADA /E-terracontrol and in aggregate within E-terra trade. E-terra trade and IPO systems responded to acceptances from a simulated balancing market and interacted with ECN’s PowerMatcher, which then controlled the generation resources in the laboratories of ICL.”

**EU-EcoGrid**

Here is an example of the VPP implement in Denmark, named EU-EcoGrid project [9]:

![Structure diagram of EU-EcoGrid project](image)

**Figure 4** – Structure diagram of EU-EcoGrid project[10]

Including 36 MW of wind power, a 16 MW biomass plant, and 2 MW Biogas, 2MW Photovoltaic (solar) plant new fleet of electric cars—will be a central control system that behaves very much like a traditional power generator. It last for 4 years and began from middle of 2011.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customers</td>
<td></td>
</tr>
<tr>
<td>Number of customers</td>
<td>~28,000</td>
</tr>
<tr>
<td>Numbers of customers</td>
<td>~300</td>
</tr>
<tr>
<td>Total energy consumed</td>
<td>268 GWh</td>
</tr>
</tbody>
</table>
### Peak load

<table>
<thead>
<tr>
<th>Energy Resource</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind power plants</td>
<td>30 MW</td>
</tr>
<tr>
<td>CHP/biomass</td>
<td>16 MW</td>
</tr>
<tr>
<td>PV (roll-out under project)</td>
<td>1.0 MW</td>
</tr>
<tr>
<td>Biogas plant</td>
<td>2.0 MW</td>
</tr>
<tr>
<td>Electric vehicles (under roll-out)</td>
<td></td>
</tr>
</tbody>
</table>

### Grid

<table>
<thead>
<tr>
<th>Grid</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 KV grid</td>
<td>131 km</td>
</tr>
<tr>
<td>Number of 60/10 KV substations</td>
<td>16</td>
</tr>
<tr>
<td>10 KV grid</td>
<td>914 km</td>
</tr>
<tr>
<td>Number of 10/0.4 KV substations</td>
<td>1006</td>
</tr>
<tr>
<td>0.4 grid</td>
<td>1.887 km</td>
</tr>
</tbody>
</table>

### Communication

<table>
<thead>
<tr>
<th>Communication</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber network between 60/10 KV subsation</td>
<td>131 km</td>
</tr>
</tbody>
</table>

### District heating

<table>
<thead>
<tr>
<th>District heating</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of district heating systems</td>
<td>5</td>
</tr>
<tr>
<td>Total heat demand (in 2007)</td>
<td>560 GWh</td>
</tr>
</tbody>
</table>

### Operation

<table>
<thead>
<tr>
<th>Operation</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal operation capability</td>
<td>Interconnected Nordel</td>
</tr>
<tr>
<td>Island operation capability</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

**Regenerative Combined Power Plant**

Here is another example that so called ‘The largest mixed-asset VPP in the world’ located in Germany[11]:

The projects are combined and monitored through an intelligent controlling system that allows operators to quickly changing power adapt to needs.

The Combined Power Plant consists of three wind parks (12.6 MW), 20 solar power plants (5.5 MW), 4 biogas systems (4.0 MW) and the pump storage Goldisthal (Output: 1.060 MW; Storage: 80 hours, i.e. 8480 MWh). Within Intelligent controlling and accurate weather forecasts allows regenerative power supply around the clock[12].
Figure 5 – Control Unit Functions of the Regenerative Combined Power Plant project

Figure 6 – GUI in the control unit[13]

**Smart Grid Gotland**

Smart Grid Gotland – electricity network for the future is a 4 years demonstration project in Sweden. It implements the concept of VPP in Demand Response Management System (DRMS) in the biggest island of Sweden, Gotland. The project has got 23 million SEK from the Swedish Energy Agency and it will start from September of 2012. It
aggregates distributed wind farm together, and balance the power between generation and consumption by battery energy storage facility or by trading the power with mainland Sweden via HVDC link [4].

Figure 7 – Gotland Smart Grid Project
3 SIMULATION OF VPP

3.1 Prototype of simulation model

As mentioned above, the VPP includes

- Power generation units
- Energy storage units
- System loads

Since the hydro power plant has reservoir, which can be regarded as storage unit. In some research, the researchers had confirmed that it is possible to balance the large wind power deviation just by control hydro power plant as storage units in Sweden. [11] The system contains 4 units, include the infinite bus representing the connecting points connected with transmission grid, hydro power plant, system load and wind farm. The system prototype comes from a small town located in the middle Sweden.

![Prototype of VPP model in simulation](image)

**Figure 8** – Prototype of VPP model in simulation

3.2 Simulation model in MATLAB

Overall system Simulink

In the MATLAB/ Simulink, the similar model was been built as the following picture shows:
The Virtual Power Plant model contains Infinite bus representing the transmission grid, a hydro power plant, a system load and a wind farm. Those units connect with each other via transmission lines.

It is a system with 4 buses located in each corner of the square. It is a ring-shape system. The power flow can go through all the bus via the cycle. Bus 1 connects with transmission grid, Bus 2 connects with hydro power plant, Bus 3 connects with dynamic system load and Bus 4 connects with the wind farm.

The control center block contains two sub systems: controller system and measurement system.
Controller system receives measurement values, then it calculates the power difference between wind farm and system load. Under different control schemes, the controller send different commands to the hydro power plant, to control the output power generated from hydro to balance the system.

Measurements block measure all the voltage and current in all buses. Also, it measures all the active power consumption in all units. It sends those real time measurement values to the controller system.

3.2.2 Illustration for blocks

Transmission grid

![Transmission Grid](image)

**Figure 11 – Transmission Grid**

It is represented by an infinite bus connected with a source without resistance and inductance. Without resistance and inductance, it represents a large transmission grid that has the constant voltage at the bus point. The circumstance of reactive power inside the VPP cannot affect the voltage at Bus 1. Nominal voltage is 33 KV.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase-to-phase rm voltage(V)</td>
<td>33 KV</td>
</tr>
<tr>
<td>Frequency(Hz)</td>
<td>50</td>
</tr>
<tr>
<td>Internal connection</td>
<td>v</td>
</tr>
<tr>
<td>Source resistance(Ohms)</td>
<td>0</td>
</tr>
<tr>
<td>Source inductance(H)</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3 – Block Parameters: Transmission Grid

The Bus bar

![Bus bar](image)

**Figure 12 – Bus bar**

It connects the unit in the square corner and the other units together via transmission line. It also measures all the voltages and currents in each bus bar and send those measurement values to the measurement system. Since nowadays the new version of Simulink doesn’t supply the bus bar block, so the bus bar block here is represented by the ‘three-phase VI measurement’ block in Simulink. By using the label of measurement value, it looks like exactly the same as the bus bar block in older Simulink software.
Table 4 – Block Parameters: Bus bar

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage measurement(V)</td>
<td>Phase-to-ground</td>
</tr>
<tr>
<td>Current measurement</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Transmission line

Figure 13 – Transmission line

It’s a middle distance transmission line model that only has resistance and inductance. The shut capacitors are neglected. The resistance and inductance are connected in parallel.

Table 5 – Block Parameters: Transmission line

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branch type</td>
<td>RL</td>
</tr>
<tr>
<td>Resistance(Ohms)</td>
<td>1</td>
</tr>
<tr>
<td>Inductance(H)</td>
<td>1e-3</td>
</tr>
</tbody>
</table>

The Hydro Plant

Figure 14 – Hydro power plant

It gets the control command from the Hydro Control System. It is represented by a synchronous machine.
The hydro power plant is represented by a synchronous machine. Its terminal voltage is under the control of excitation system. So the voltage of its terminal voltage is a constant value. And the terminal voltage is being set as 1 pu. The d-axis stator voltage and q-axis stator voltage comes from the measurement port of synchronous machine, and being sent to the excitation system. Since there is not voltage stabilizer being used here, so the ‘vstab’ port is connected with the ground.

To simplify the control of rotor angle, automatic generator controller is not being added here. The output of active power is controlled by the command send from control center directly.

The initial value of synchronous machine has been optimized by using the ‘Powergui Machine Initialization Tool’.

Table 6 – Block Parameters: Synchronous Machine

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical input</td>
<td>Mechanical power Pm</td>
</tr>
<tr>
<td>Rotor type</td>
<td>Salient-pole</td>
</tr>
<tr>
<td>Nominal power (VA), line to line voltage (Vrms) and frequency(Hz)</td>
<td>1E7, 33000, 50</td>
</tr>
<tr>
<td>Stator[Rs LI Lmd Lmq] (pu)</td>
<td>2.85E-3, 0.114, 1.19, 0.36</td>
</tr>
</tbody>
</table>
Field [ Rf Llfld ] (pu) 5.79E-04, 0.114
Dampers [ Rkd Llkd Rkq1 Llkq1 ] (pu) 1.17E-02, 0.182, 1.97E-02, 0.0384
Inertia coefficient, friction factor, pole pairs [ H(s) F(pu) p() ] 0.7 0 20

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-pass filter time constant Tr(s)</td>
<td>20e-3</td>
</tr>
<tr>
<td>Regulator gain and time constant [ Ka() Ta(s) ]</td>
<td>300, 0.001</td>
</tr>
<tr>
<td>Exciter [ Ke() Te(s) ]</td>
<td>1, 0</td>
</tr>
<tr>
<td>Transient gain reduction [ Tb(s) Tc(s) ]</td>
<td>0, 0</td>
</tr>
<tr>
<td>Damping filter gain and time constant [ Kf() Tr(s) ]</td>
<td>0.001, 0.1</td>
</tr>
<tr>
<td>Regulator output limits and gain [ Efmin, Efmax (pu), Kp() ]</td>
<td>-11.5, 11.5, 0</td>
</tr>
<tr>
<td>Initial values of terminal voltage and field voltage [ Vt0 (pu) Vf0(pu) ]</td>
<td>1.142611</td>
</tr>
</tbody>
</table>

The Load

![System Load Diagram](image)

Figure 16 – Load

It is a dynamic load block in Simulink. The tag in the upper right corner indicates the real history data from a ‘mat.’ file in the same path, which has 1440 data points represent total 1440 minutes in 24 hours in one single day. Since the reactive power will not being considered in this research, so the reactive output power has been set to 0 Var.
The command sent from control center goes into the PQ port in the upper right corner. Its consumption of active power follows the command. When the value of signal is positive, it consumes power. When the value of signal is negative, it generates power. Here it represents the load, so the signal is always a positive value.

The nominal voltage value is 33 KV and the nominal frequency is 50 Hz.

The Wind Farm

Similarly, it is being represented by a dynamic load block like the dynamic system load. It reads the negative data value (so it produce power instead of consume power) from a 'mat.' file. The nominal voltage value is 33 KV and the nominal frequency is 50 Hz.
The Measurements system

![Diagram of Measurements block](image)

**Figure 19 – Measurements block**

It gets data from bus bar block, including current and voltage. Within 3-phase PQ measurement block it can calculate the active power and reactive power, then sent those measurement data into the controller system. Also, the scopes in this measurement subsystem supply a vivid window to present the results. It can save the data from the scope to a ‘mat.’ file in the same path.

In detail, it measures the active power and reactive power goes through Bus 1, Bus 2, Bus 3 and Bus 4. It also observes the active power go through transmission grid, active power consumption of system load, active power generation of wind farm and active output power from hydro power plant by a 4 channels’ scope.
The Controller System

![Controller block diagram](image)

**Figure 21** – Controller block

Its architecture structure depends on the control scheme, it can be a run-time control, it can be a controller with moving average method or it can be a controller within both moving average method and forecast method together.

**Run time controller block**

![Run time control block diagram](image)

**Figure 22** – Run time control block

The controller system reads the measurement values of active generation power of wind farm and active power consumption of system load from measurement system, and then it calculates the difference between those active power values. Without any advanced control process, neither moving average process, nor forecast compensation process. It will be changed to pu value and then sent to the hydro power plant directly.

Since the hydro power can not generate infinite active power, there is a limit. Here the lower limit is 0 MW which means the hydro power can stop when there is no need to use hydro power plant to balance the system load consumption. The upper limit is 6.262 MW. When the calculated value over this upper limit, the transmission grid needs to participate in balance of active power.

To decrease the initial hydro turbine start up turbulence effects, there is a switch in the command channel. For the first 20 sampling interval, it gives hydro power plant a constant initial value and the calculated channel is blocked. From the 21st sampling interval, the channel is being activated. So the command comes from the calculated result.

**Moving average controller block**
Similar to the run time control block, it has almost the same structure of run time controller. The only difference is that it contains two moving average controllers (MA Controller) between the measurement value inputs to the difference calculator. The additional controller is moving average controller.

As can see from the moving average controller, its window size is 10. The inputs data go through a delay line block, which delays the input data flow by 1, 2, 3 … 10 sampling intervals respectively and the order is up-down wise. Then the delayed data are summed up by a sum block. Later on, the sum is being divided by the size of moving average window via a gain block. Until now, the moving average process is done. Also, it includes a switch to decrease the effect comes from turbine start up turbulence.

Note: the window size is not only 10. It can be adjusted according to different analysis goals.
Forecast compensation controller block

![Diagram of Forecast Compensation Controller Block]

**Figure 25** – Forecast compensation control block

Similar to the moving average controller, it also contains two moving average controller and a switch.

The additional blocks here are the introduction of forecast block and weight factor blocks. The forecast input doesn't have a moving average controller. It is a combination with forecast inputs of system load and moving average input of system load. The weight factors determine how much percent the forecast input and moving average inputs can be used in the controlling of hydro power plant.

### 3.3 Data usage for simulation

The history data on hand is the load, wind data from the year 2009 and 2010 in minutes. Arbitrally, the latest month being considered to use in the simulation, the December in 2010.

Since the minutes’ data is been considered in the simulation to simulate the real system, then one day is enough for the software to run within the 1440 (1440 minutes = 24 hours = 1 day) data points. It takes around 10 minutes for the Simulink model to run.

How to select one day from December 2010 is depends on the observation aspect. Due to the limits of hydro controllably that it cannot produce more than 6.262 MW to balance the system. So for the observation’s point of view, it's better to choose a day that the hydro power plant can participate in balancing the system at most.

Finally, 20th, December 2010 is being chosen, since it has the best observe ability in December 2010 that the difference between wind farm output and load consumption almost in the range between 0 MW to 6.262 MW.
3.4 Data exchange between the simulation model and external database

Those data comes from a company in the given town located in middle of Sweden. Their sampling interval is in minutes.

By setting the model properties, it is easy to insert history data into the simulation model when the model starts as well as save the simulation results in external database when the model stops.

![Model Properties](image)

**Figure 27** – Callback functions

Before the model start, there is a ‘callback-Initial’ function set up by the model properties. It loads the real history data from a ‘mat.’ file located in the external database into the workspace of Simulink. Then the data will be inserted into the model by indication of tags related to the same variables in workspace.

Similarly when the model stopped, with the help of ‘callback-Stop’ function set up by the model properties will save those results that had been saved in the scope to the external database.
Working flow chart:

![Flow chart for data usage in simulation.](image)

**Figure 28** – Flow chart for data usage in simulation.
4 CONTROL OF VPP

4.1 Backgrounds

How the simulation system works basically

If the difference between active power consumption of load and generation of wind farm is higher than the maximum production capacity of hydro power plant, then the grid needs to send power into the VPP system to compensate the power shortage. And vice versa, if the power generated from the wind farm is higher than the load consumption, then the surplus power will be sent to the grid to keep balance of power inside the VPP. There is a limited range for the maximum output of hydro power plant, which is been set up between 0 MW - 6.262 MW.

In this research, only the balance of active power is being considered.

Accuracy and error issues

However, how much the hydro needs produce depends on the command send to the hydro plant. There will be some problems with the command signal. Due to the accuracy problems [15] in measurement devices and error in the information transmission [16], it can leads to noise in the command signal and then generate overshoot problems in the power transmission and turbulence in controlling hydro turbine.

![Figure 29 – Noise in the signal](image)

Hydro power plant response issues

There are quite a lot of the mechanical devices in the hydro power plant. For example, the gate server motors, the shaft devices and the automatic generator controller. When controlling the hydro power output, some of the mechanical devices will leads to the delay in the hydro power plant output response due to the mechanical inertia. Those mechanical devices can not stand with frequently noise in the control command. So smoothly control of hydro power plant is quite important.
4.2 Control Goals

The control schemes here are based on runtime control method, moving average method and forecast control method respectively. The control goal is to decrease the effect of VPP on the transmission grid. In other words, to avoid larger deviation in the exchange power to the transmission grid. At the same time, hydro turbine should be controlled in an optimized way without large turbulences.

In sum the control goals are:

- Decrease the effects of VPP on the transmission grid
- Optimized control the hydro turbine

![Figure 30 – Observed blocks in the simulation](image)

4.3 Control schemes

Basically, the hydro power plant is responsible for balancing the active power between the wind farm and dynamic load. Since there is a limit for the hydro turbine output, the rest of either power shortage or surplus power need to be compensated by the grid. This is the fundamental control scheme, so-called real-time control scheme. Moreover, due to the accuracy problems in measurement devices, the noise in the information transmission channel that leads to measurement error and noise, which also result in overshoot problems in the power transmission and turbulence in controlling hydro turbine. The advanced control schemes here are based on the moving average control method and forecast compensation control method. The forecast compensation control method use the 24 hours ahead load forecasting data to compensate the moving averaged data. Those forecasting data comes from the Artificial Neural Network trained by history data.
Run time control

![Diagram](image)

**Figure 31** – Run time control illustration

Run time control method is the fundamental method that uses the raw data from measurement devices, the difference between active generation power of wind farm and active consumption power of system load is being calculated. The control center directly sends the command to the hydro power plant with the difference value calculated above. In this case, the output power of hydro is expected to compensate the shortage power of wind farm.

With the limits of hydro output, hydro power cannot balance infinite power shortage between the wind farm and load consumption. So the rest of power will comes from the transmission grid.

Without any complicate controller, just use the original data comes from the measurement units, which has lots of accuracy and noise issues.

Moving average control

Introduction of Moving Average

The Moving Average is the mathematical results that calculated by averaging a number of past data points. [17]

Usually, Moving Average also been called as Run Time Window, which means a window that will run with the data within a specific window size.

From those pictures, it is easy to see how it goes.
As the figure XX shows, the window size of this moving average method is 7. At the time \( t=0 \) s, it sum the past 7 data points up, 6, 7, 8, 9, 0, 1 and 2. Now the result is the averaging sum of those data, 4.714. At the time \( t=1 \) s, the average window moves forward with step of 1 data point. Similarly, it sum the past data points up, 7, 8, 9, 0, 1, 2 and 3. Now the result is the average sum of those new data, 4.286. At the time \( t=2 \) s, the window will moves forward one step. The window always running, that is why it also being called run time window.

**Characteristics of Moving Average**

Seen from the above example, it is easy to make conclusion that the moving average can smooth the data flow. For example, from \( t=0 \) s to \( t=1 \) s, the data goes from 2 to 3. But with moving average process, the data only goes from 4.714 to 4.286 which have lower difference.

However, the trend of data flow is opposite. The real data flow goes up from 2 to 3, but the moving averaged data flow goes down from 4.714 to 4.286. The reason leads to this delay is because there is statistic inertia (like inertia in the physics) in the moving average. When calculate the values, it always consider previous data points together, it is like history burden that moving average cannot keep follow the new trend of real data flow. So sometimes it has the trend opposite to the real data flow.
As the figure shows, moving averaged data has a specific scale of delay when the window moves. And the larger the window size, the longer delay it has. Usually, it is a tradeoff between how smooth it is and how long it delays.

Moving Average control in this paper:
Add moving average window (run time window) in the channel transmitting commands, to smooth the output commands before it goes into the hydro turbine control unite.

The benefit of using moving average is to smooth the data flow. By using those smoothed data to control the hydro power plant, it can reduce the turbulence in the hydro turbine due to large deviation in the data samples.

Forecast Compensation Control

Introduction of Forecast compensation control
Since the moving average has the inherent drawback of delay, so it cannot smooth the exchange power between inside and outside of VPP. Here another idea shows up, to use the history data to predict the 24 h ahead load consumption. Of course it has not inherent delay but deviations due to the accuracy issues. So when combine the forecast data without inherent delay and the moving average data with the delay to run the VPP, probably it will gives better control results.

Introduction of forecast compensation methods
Why forecast the load
The forecast scenario can be implemented in wind power, hydro power or load power in research scope. However, since the forecast of load can achieve higher accuracy than forecasting the others like wind [18], then only forecast the load here can make the forecast control method competitive.

How to forecast the load
Lots of methods have been proposed from the middle of 20th century, over all speaking, the most popular one is Artificial Neural Network. And the most classic successful implement of this method was conducted by D.C. Park, et al in 1991 in University of Washington. [19]

In this research, the classic method mentioned in above is been modified according to the specific needs. The Artificial Neural Network model in this paper is been explained in detail in the following sections.

How compensate the moving average control method

![Diagram of forecast compensation control](image)

Where \(a\%+b\% = 100\%\).
From the figure above, it is easy to know that moving average data is the real time data, and the forecast data is the known data that had got before 20th December of 2010.

Due to the inherent drawback of moving average, statistic inertia, so the data flow has a delay compared with the real data flow, which leads to large deviations in the exchange power between inside and outside VPP. So, the forecast method been used in this case to compensated the inertia. The 24 h ahead forecast method gives a better trend curve for the data flow.

**Introduction of Artificial Neural Network**

What is ANN

‘Artificial neural networks, originally developed to mimic basic biological neural systems- the human brain particularly, are composed of a number of interconnected simple processing elements called neurons or nodes. Each note receives an input signal which is the total ‘information’ from other nodes or external stimuli, process it locally through an activation or transfer function and produces a transformed output signal to other nodes or external outputs’ says in Guoqiang Zhang’s paper[20]

It is a method been proposed in 1980s. After several decades, a large amount of researchers had developed it into a more sophisticated one. It has showed a significant success on forecasting area.

Basic elements are input layer, hidden layer and output layer.

In mathematical language, the ANN is trying to find the appropriate mathematical function to express the relationship between the input data and output data.

![Artificial Neural Network structure](image)
CHAPTER 4 CONTROL OF VPP

Figure 37 – Black box of the ANN structure

Figure 38 – Mathematical structure of ANN

The mathematical expression is [20]

\[ y = f \left( \sum_{i=0}^{n} w_i x_i \right) \]

where the \( w \) is the weight factor for each input, the \( x \) is the input data, \( y \) is the final output, the \( f(x) \) is the transfer function.

Commonly, the transfer function is sigmoid (logistic) function \( f(x) = \left( 1 + e^{-x} \right)^{-1} \)

Then we insert both input data and output data, to calculate the weight value for each connecting line between the nodes, in order to minimize the sum of the errors between the output data resulting value when using the neural network. It is been called ‘Train network’ [20]:

\[ E = \frac{1}{2} \sum_{i=1}^{N} (y_i - a_i)^2 \]

Where the \( y_i \) is the resulting value when using the trained network, \( a_i \) is the actual output data. \( \frac{1}{2} \) is for simplify the derivatives calculation in the training algorithm.

Via amount of iterations, we can get the most appropriate function, hence the neural network has been established.
The basic structure of ANN is the Multi-Layer Perceptrons (MLP), the first layer or the so called 'lowest layer' is an layer contains input information as external information. The last or the so called 'highest layer' is a layer gives output information that the solution is obtained for the problem regarded in the neural network.

**How to build it**

**Parameters**

Before building the ANN, those data need to be prepared:

- Input data (those data in will been inserted into the model to get the results)
- Output data (those data expected to get after the model calculation)

Also, those parameters need to be specified for the ANN structure.

- The nodes in input layer (usually is equal to the input data width)
- The nodes in output layer (usually depends on the variables been focus on)
- The numbers of the hidden layer (One layer is enough for most of the forecast model [20])
- The nodes in the hidden layer (not specific rules, vary from case to case)
- The transfer function (most common one is logistic function)

Usually, the structure of the ANN is been built by try and trial method, since there is not absolute exact principle for load forecast [20]. And it is vary a bit depends on the sample data as well. For example, the fewer the nodes in the hidden layer, the more generalization ability it has. But it is hard for the network to learn the data. And if the data has less generalization characteristics, then it will be a not so useful model.

**Data preparation**

Usually, the input data are some related factor that will affect the output and those factors can be defined before the event happen. Like people can use the weather data for tomorrow according to weather forecast as part of the input to forecast the load consumption for tomorrow. Those data need to be collected and changed to a specific format for ANN.

When had done preparing of the data, then it is necessary to separate it into two groups, training group and testing group.
Training

Within the training group including training inputs and training outputs, then insert those data into the ANN model built before, so the ANN can train and adjust the weights factor in each inputs channel to make sure the lowest error (difference between training results and output data) can be achieved.

The most popular method to find the best or better weights for the ANN is called, backpropagation algorithm that based on a gradient steepest descent method basically.

(For the details, please refer to the relevant paper [21]

Within large amount of iterations, the ANN model has been carried out. Usually, the structure of the ANN is not been fixed. For example, the nodes in the hidden layer can be varying from n to 2n+1, where n is the number of the input nodes.

Testing

However, as mentioned before, the ideal model structure is come out with lots of times of try and trial. Even though the trained ANN models have being carried out, the test procedure needs to be done before the final ANN model been established.

Within the testing group data, it is possible to test which models is the best (or in the other words, what is the best number of the hidden nodes). By inserting the testing input data into the ANN models, the results will be come out. Then now the error between the results data and testing output data is the criteria for choosing the best ANN model.

Summary for establishing of ANN

Here are the steps of how to build an artificial neural network for forecast in this paper.

1. Get the sampling data, like temperature data and load consumption data.
2. Divide the data into two groups, training group and testing group.
3. Decide the number of inputs nodes and output nodes according to the data and forecast goals.
4. Decide the hidden layers.
5. Decide numbers of hidden nodes, usually it is a range.
6. Decide the transfer function.
7. Train the data and test it, choose the structure with the best testing results, then the numbers of hidden nodes is specified.

Here is the flow chart of building

![Diagram of building ANN](image)

*Numbers of hidden nodes vary from $n:2n+1$*

*Choose the best ANN structure (NO. of hidden nodes) from the test errors*

**Figure 40** – Working flow of building ANN
4.4 Data usage in different controlling methods

The previous section has mentioned about the data usage in simulation, which is a general illustration for the data being used in the simulation process that the 20th of December in 2010 is being observed. However, it is still necessary to clarify the difference between data sources being used for different controlling methods receptively.

For example, for the run time control and moving average control methods, only 20th December’s data is being used, they are kind of real time control that running with real time data from some perspective. However, for the forecast compensation control method, it not only needs the data in 20th December of 2010, but also it needs the previous history data to forecast 20th December load.

Figure 41 – Data usage in different control schemes
5 RESULTS AND ANALYZE

5.1 Forecasting results and analysis

Data preparation for forecast

Weather data
In this research only the load is been consider to forecast in this paper and the data on hand is comes from a town located in the middle of Sweden. In forecasting of load, the temperature is one of critical important factors will affect the load. The temperature data comes from the weather information website [22]

![Figure 42 – Scatter diagram of temperature and load](image)

When drawing the scatter diagram of the local load and temperature (dry bulb temperature) between 2009 and 2010, it shows a strong relationship between each other.
From the diagram above, it is quite clear that when the temperature goes down, the load will increase in a nearly linear relationship, and vice versa. It is the hint that it will possible to forecast the load with the temperature data accurately.

**Input data**

![Input data structure](image)

- **Dry bulb temperature**
- **Dew point temperature**
- **Hour of day**
- **Day of week**
- **Holiday/weekend indicator (0 or 1)**
- **Previous 24-hr average load**
- **24-hr lagged load**
- **168-hr (previous week) lagged load**

Data size: $8 \times 17520$

**2009 : 2010, 2 years’ hourly data**

*Note: since with the limitation of computer’s memory, it’s hard to train the minute data in 2 years. So the minutes data been adjust into the hourly data first by $P_{\text{hour}} = P_{\text{minute}}$, where $i = j / 60$.*

The holidays and weekend data comes from the date and holidays website [23]

**Output data**
Output data structure

Hourly load

| 1 | 2 | 3 | ... | 17518 | 17519 | 17520 |

2009 : 2010, 2 years’ hourly data
Data size: 1*17520

Figure 44 – Structure of output data for ANN

Dividing sampling data into two groups

Dividing the sample data

2009 year & 2010 1st Jan - 12th Dec
Training Group

Previous week

2010 Dec 19th
Testing Group

2010 Dec 20th
Simulation day

Figure 45 – Dividing the sample data to two groups for ANN

ANN Model for forecasting the load in MATLAB

With the Matlab, Neural Network can be built quite easily. Just by call a Neural Network Toolbox, set up parameters like transfer function, hidden layers, number of nodes in the hidden layers, and then it can automatically train the weight factor.
Figure 46 – Matlab Neural Network Fitting tool

Also, MATLAB supply a webinar, introducing about how to build the ANN for forecasting of load. Recorded Webinar: Electricity Load and Price Forecasting with MATLAB [18]

In the example shows in the webinar, the input data structure is
We use the classic model in training the network with those parameters:

Table 2. Parameters of the ANN

<table>
<thead>
<tr>
<th>Input layer nodes ($n_i$)</th>
<th>8</th>
<th>Same as input data, $n_i = 8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hidden layers</td>
<td>1</td>
<td>One is enough</td>
</tr>
<tr>
<td>Nodes in hidden layer</td>
<td>8-17</td>
<td>It vary from, $n_i : 2n_i + 1$</td>
</tr>
<tr>
<td>Output layer nodes ($n_o$)</td>
<td>1</td>
<td>Only load data needed, $n_o = 1$</td>
</tr>
<tr>
<td>Transfer function</td>
<td>Logistic</td>
<td></td>
</tr>
</tbody>
</table>

To find out the best number of hidden nodes which vary from 8 - 17, the test group being checked.

From the test group, the Mean Absolute Percentage Error (MAPE) is the only criterion to judge which model is the best.
Testing results

Table 9 – Results from different structures of ANN for training

<table>
<thead>
<tr>
<th>Test</th>
<th>Node 8</th>
<th>Node 9</th>
<th>Node 10</th>
<th>Node 11</th>
<th>Node 12</th>
<th>Node 13</th>
<th>Node 14</th>
<th>Node 15</th>
<th>Node 16</th>
<th>Node 17</th>
<th>Error Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>7.6</td>
<td>8.1</td>
<td>11</td>
<td>7.8</td>
<td>13</td>
<td>8.0</td>
<td>7.1</td>
<td>7.4</td>
<td>7.2</td>
<td>MAPE</td>
</tr>
<tr>
<td>2</td>
<td>7.7</td>
<td>7.8</td>
<td>7.4</td>
<td>7.5</td>
<td>10</td>
<td>7.8</td>
<td>7.6</td>
<td>7.8</td>
<td>7.3</td>
<td>8.3</td>
<td>MAPE</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>8.0</td>
<td>7.9</td>
<td>7.6</td>
<td>7.6</td>
<td>7.7</td>
<td>16</td>
<td>7.2</td>
<td>6.9</td>
<td>7.6</td>
<td>MAPE</td>
</tr>
<tr>
<td>4</td>
<td>7.2</td>
<td>7.8</td>
<td>7.8</td>
<td>7.5</td>
<td>7.3</td>
<td>7.0</td>
<td>15</td>
<td>7.7</td>
<td>7.8</td>
<td>6.9</td>
<td>MAPE</td>
</tr>
<tr>
<td>5</td>
<td>7.0</td>
<td>7.3</td>
<td>7.6</td>
<td>7.5</td>
<td>6.5</td>
<td>7.8</td>
<td>7.3</td>
<td>7.7</td>
<td>7.4</td>
<td>17</td>
<td>MAPE</td>
</tr>
</tbody>
</table>

As can see from the 5th test, the 12 nodes in the hidden layer is the best from the entire test, it just 6.5% in the mean absolute percentage errors.

So now, the final model has been established.

Table 10 – Parameters of best structure of ANN

<table>
<thead>
<tr>
<th>Input layer nodes ( n_i ):</th>
<th>8</th>
<th>Same as input data, ( n_i = 8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hidden layers:</td>
<td>1</td>
<td>One is enough</td>
</tr>
<tr>
<td>Nodes in hidden layer:</td>
<td>12</td>
<td>According to the test results</td>
</tr>
<tr>
<td>Output layer nodes ( n_o ):</td>
<td>1</td>
<td>Only load data needed, ( n_o = 1 )</td>
</tr>
<tr>
<td>Transfer function</td>
<td>Logistic</td>
<td></td>
</tr>
</tbody>
</table>

With this ANN model, the forecast load data can be conducted and it shows only 2.4829% of Mean Absolute Percentage Error, as the diagram shows below.
5.2 Control results and analysis

Criterion for control goals:
For consider which control method is the best. We introduce those criterions
Mean Absolute Percentage Error in the power of grid.
The reference is the zero, since the lowest variations in the exchange power between inside and outside the VPP is what had been considered.
CHAPTER 5 RESULTS AND ANALYZE

\[ Error_{\text{grid}} = \frac{100}{n} \sum_{i} |Power_{\text{grid}}(i)| \% \]

Mean Absolute Percentage Error in the power of hydro

The reference is the smoothed curve of the hydro power.

For overall criterion, \( Criterion_{\text{overall}} = Error_{\text{grid}} + Error_{\text{hydro}} \)

Definition of best control model that can both smooth the exchange power and the output power in the hydro: The lowest criterion, the best control it shows.

However, since the size of those error are not in the same level. For example,

\[ Error_{\text{grid}} = a \times 10^8 \]

\[ Error_{\text{hydro}} = f \times 10^8 \]

Where 'a', 'b', 'c', 'd', 'e', 'f', 'g', 'h', 'i' and 'j' are given values.

So for fairly take care of those criterion while to make sure it fulfills the control goals. The overall criterion been modified as

\[ Criterion_{\text{overall}} = Error_{\text{grid}} \times 10^{-9} + Error_{\text{hydro}} \times 10^{-8} \]
First Round
Runtime control and Moving average control

Figure 51 – Results of run time and moving average
As can see from the table above, the Run Time Control method is the best in smoothing the exchange power between inside and outside the VPP system. On the other hand, it is the worst in smoothing the hydro power plant output.

As the moving average window size increase, it gives better effect in smoothing the hydro power plant output but it also results in worse effect in smoothing the exchange power between inside and outside the VPP system.

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Error_{\text{grid}} (%)</th>
<th>Error_{\text{hydro}} (%)</th>
<th>Criterion_{\text{overall}} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run Time</td>
<td>3.1393</td>
<td>2.0673</td>
<td>5.2066</td>
</tr>
<tr>
<td>Moving Average (size=10)</td>
<td>3.1719</td>
<td>1.9125</td>
<td>5.0844</td>
</tr>
<tr>
<td>Moving Average (size=20)</td>
<td>3.2785</td>
<td>1.6972</td>
<td>4.9757</td>
</tr>
<tr>
<td>Moving Average (size=30)</td>
<td>3.3911</td>
<td>1.5288</td>
<td>4.9199</td>
</tr>
<tr>
<td>Moving Average (size=40)</td>
<td>3.507</td>
<td>1.4208</td>
<td>4.9278</td>
</tr>
<tr>
<td>Moving Average (size=50)</td>
<td>3.6252</td>
<td>1.3562</td>
<td>4.9814</td>
</tr>
<tr>
<td>Moving Average (size=100)</td>
<td>4.2166</td>
<td>1.2714</td>
<td>5.488</td>
</tr>
</tbody>
</table>
The best control method that has the overall positive effects for control goal is when the moving average window with size to be 30. And in this case, the moving average method improved the results by \((5.2066-4.9199)/5.2066=55.1\%\) when compare with run-time control method.

Forecast (only) control
Figure 54 – Results of only forecast control and the others control schemes
As can be seen from the diagram above, the barely forecast control has relatively higher deviations in the exchange power and hydro output even though the mean absolute percentage error of the forecast just around 3 (%). The error between the forecast and the real data flow is even higher than the error due to the statistic inertia of moving average within size of 100.

However, as the figure 55 shows, the forecast data has better behavior in catching the turn points than the moving average method.

**Forecast Compensation Control**

Since the forecast has the better behavior in catching the turn points, than here comes up a new method that combining the moving average and forecast method together.

**Table 12 – Results of forecast compensate control**

<table>
<thead>
<tr>
<th>Control method</th>
<th>$\text{Error}_{\text{grid}}$ (%)</th>
<th>$\text{Error}_{\text{hydro}}$ (%)</th>
<th>$\text{Criterion}_{\text{overall}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moving Average (size=100)</td>
<td>4.2166</td>
<td>1.2714</td>
<td>5.488</td>
</tr>
<tr>
<td>Moving Average (size=30)</td>
<td>3.3911</td>
<td>1.5288</td>
<td>4.9199</td>
</tr>
<tr>
<td>Forecast compensation*</td>
<td>3.3826</td>
<td>1.5341</td>
<td>4.9167</td>
</tr>
<tr>
<td>Run Time Control</td>
<td>3.1393</td>
<td>2.0673</td>
<td>5.2066</td>
</tr>
</tbody>
</table>
*Note: the Forecast compensation is $\frac{1}{2}P_{\text{forecast}} + 0.99\% P_{\text{load}}$ which gives the best control results.

Forecast did works and it improve the results by $(4.9199 - 4.9167)/4.9199 = 0.6 \%$ when compare with moving average control method. Compare with the moving average which had improve it by 55.1 \%, the improvement led by forecast compensation is not so significant.

**Second Round**

**To find the best Moving Average Control method**

As the moving average 30 probably is not the best size for the control methods. So we can try to find the best moving average size, and then using the forecast to compensate it.

<table>
<thead>
<tr>
<th>MA</th>
<th>$E_{\text{grid}}$ (%)</th>
<th>$E_{\text{hydro}}$ (%)</th>
<th>$C_{\text{overall}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>3.3681</td>
<td>1.5581</td>
<td>4.9262</td>
</tr>
<tr>
<td>29</td>
<td>3.3795</td>
<td>1.5425</td>
<td>4.922</td>
</tr>
<tr>
<td>30</td>
<td>3.3911</td>
<td>1.5288</td>
<td>4.9199</td>
</tr>
<tr>
<td>31</td>
<td>3.4025</td>
<td>1.5162</td>
<td>4.9187</td>
</tr>
<tr>
<td>32</td>
<td>3.414</td>
<td>1.5031</td>
<td>4.9171</td>
</tr>
<tr>
<td>33</td>
<td>3.4256</td>
<td>1.4918</td>
<td>4.9174</td>
</tr>
<tr>
<td>34</td>
<td>3.4371</td>
<td>1.48</td>
<td>4.9171</td>
</tr>
<tr>
<td>35</td>
<td>3.4487</td>
<td>1.4682</td>
<td>4.9169</td>
</tr>
<tr>
<td>36</td>
<td>3.4603</td>
<td>1.4591</td>
<td>4.9194</td>
</tr>
<tr>
<td>37</td>
<td>3.4864</td>
<td>1.4452</td>
<td>4.9316</td>
</tr>
</tbody>
</table>

**Figure 56** – Overall error in different moving average control schemes

- 48 -
From the table, it shows when the window size of moving average is 35, it has the best effects for fulfill the control goals. It improve the run time control results by 

\[
\frac{(5.2066-4.9169)}{5.2066}=55.6 \text{‰ (per mille)}
\]

To find the best compensation factor with the best Moving Average Control scheme.

![Figure 57 – Results of forecast compensation control and other control schemes](image-url)
Figure 58 – Results of forecast compensation control and other control schemes (zoom in)

For the forecast compensation model, the compensate factor can be vary from 1(100%) to 0 (0%),

<table>
<thead>
<tr>
<th>Forecast_35 (%)</th>
<th>$\text{Error}_{\text{grid}}$ (%)</th>
<th>$\text{Error}_{\text{hydro}}$ (%)</th>
<th>Overall Criterion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>5.2938</td>
<td>1.4327</td>
<td>6.7265</td>
</tr>
<tr>
<td>10</td>
<td>3.6599</td>
<td>1.4647</td>
<td>5.1246</td>
</tr>
<tr>
<td>5</td>
<td>3.4775</td>
<td>1.4695</td>
<td>4.947</td>
</tr>
<tr>
<td>1</td>
<td>3.4402</td>
<td>1.4759</td>
<td>4.9161</td>
</tr>
<tr>
<td>0.5</td>
<td>3.4438</td>
<td>1.4766</td>
<td>4.9204</td>
</tr>
<tr>
<td>0.1</td>
<td>3.4475</td>
<td>1.4777</td>
<td>4.9252</td>
</tr>
</tbody>
</table>
Figure 59 – Overall errors of forecast compensation control with different compensate factor

So let’s see how much we can compensate this control scheme by using forecast.

Here it can be almost said that the lower the forecast compensate the Moving average, the best results it shows. It didn’t change so much in the end. \( \frac{4.9161 - 4.9169}{4.9169} = 0.163\% \). Almost means the forecast compensation does not have significant benefits for control.
6 CONCLUSION

From this paper, the Virtual Power Plant concept and architecture was been presented. Virtual Power Plant will supply a new idea to encourage consumers to participate the electricity market within renewable energy.

Three control schemes had been conducted on the simulation model, to smoothly control hydro power plant in Virtual power plant.

The run-time control has the lowest variation in the exchange power between inside and outside of virtual power plant since there is not statistic inertia within the measurements data. However, the smoothly control of hydro power plant cannot be achieved since the large deviation from the raw data.

The moving average control method has significant advantage in smooth the data flow with frequently deviation. But the more smoothed the curve will be, the more statistic inertia it has.

The forecast method, using previous data to predict 24h ahead load, can achieve satisfied accuracy. It can control the hydro turbine quite smoothly, but when run it into minutes, the small errors due to the accuracy issue of forecast can results in higher errors in the command for output power of hydro turbine. It doesn’t supply a significant improvement when compared with moving average control. Overall speaking, the forecast compensation control scheme supplies the best control model according the simulated results in this paper.

Table of the results from different control scheme

<table>
<thead>
<tr>
<th>Control scheme</th>
<th>Error_{grid} (%)</th>
<th>Error_{hydro} (%)</th>
<th>Criterion_{overall} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moving Average (size=35)</td>
<td>3.4487</td>
<td>1.4682</td>
<td>4.9169</td>
</tr>
<tr>
<td>Forecast compensation*</td>
<td>3.4402</td>
<td>1.4759</td>
<td>4.9161</td>
</tr>
<tr>
<td>Run Time Control</td>
<td>3.1393</td>
<td>2.0673</td>
<td>5.2066</td>
</tr>
</tbody>
</table>

The simulation model has been build based on the Virtual Power Plant concept and the power generation circumstance in a given town of Sweden. From the simulation platform, a more sophisticate model can be introduced by later researches.

Information and Communication Technology (ICT) plays a vital role here, for the real time control of Virtual Power Plant, its perfect if there is neither data loses nor noise when transmission the information like measurement data.
7 FUTURE WORK

For the simulation model, the wind farm can be replaced by an induction machine as the most common model in the simulation. Also, other types of DER can be added into the model, like solar power, biomass power plant to make it has more diversity.

The forecast method in this research can be modified into a more robust one. For example, the temperature data from the weather information website is the history data. It is not the real forecast data since 20th December of 2010 is already given. Usually the 24 hours ahead temperature data is not 100% accurate. So the forecast result from this paper is the ideal value. So to build a perfect structure of Artificial Neural Network can improve the research a lot.

Also, the weight factors for the error in the power grid and in the hydro power is the same, probably a more complicated and exact weight factors based on further test and analysis can be introduced to make it fair enough to compare those two criterion.

For the moving average, it uses the simplest way: sum up and then average them. However, there are more calculation way can be introduced. Like exponent moving average method, probably they will give it better control results. A further research can be conducted later.

For the way using forecast value to compensate moving average, probably there has some more sophisticated methods instead of simply sum them together. For example, to use forecast method to detect the turning point, and then drag the moving averaged data flow back within a certain period, to optimistically reduce the delay leads by moving average and the error due to the forecast error.

Also, there could be another way to forecast both load and wind power together, than either only using those pre-known forecast data to control the virtual power plant, or compensate them by some other methods.

The reactive power can be considered as the further step of research, and then the voltage will be another criterion for control results.
8 REFERENCES


