# The effect of voltage control response characteristics of wind plants on damping of inter-area power oscillations

**(Part 1 Report of Vindforsk Project V-369)**

Elforsk rapport 13:01

Nayeem R. Ullah, Math Bollen, STRI

January 2013

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# Preface

Sweden and other Nordic countries have ambitious renewable energy source (RES) integration target. This will represent a significant share of wind power in the future generation mix of Nordic countries.

From a power system point of view, total understanding of technical impacts of this new generation source on the existing power system is vital to ensure a secure and reliable operation of the power system. In a higher wind power penetration scenario, wind power plants will need to contribute to system voltage and frequency control support, which is quite obvious and logical.

In order to identify the possible impact of large scale wind power integration and to recommend on possible approaches to manage the impact the project described in this report was carried out with the research program Vindforsk III as project V-369 "PosStaWind".

The project consists of three parts focusing on different aspects of impact of wind power on the angular, frequency and voltage stability of a power system.

This report consist the report for part 1 of the project. A summary report for all three parts of the project is available as in Elforsk report 13:04.

The project is financed by Vindforsk III with substantial initial funding from the power system operators in Finland, Norway and Sweden, Fingrid, Statnett and Swedish National Grid.

Vindforsk-III is funded by ABB, Arise windpower, AQ System, E.ON Elnät, E.ON Vind Sverige, Energi Norge, Falkenberg Energi, Fortum, Fred. Olsen Renewables, Gothia Vind, Göteborg Energi, HS Kraft, Jämtkraft, Karlstads Energi, Luleå Energi, Mälarenergi, o2 Vindkompaniet, Rabbalshede Kraft, Skellefteå Kraft, Statkraft, Sena Renewable, Svenska kraftnät, Tekniska Verken i Linköping, Triventus, Wallenstam, Varberg Energi, Vattenfall Vindkraft, Vestas Northern Europe, Öresundskraft and the Swedish Energy Agency.

The work has been carried out by STRI with Nayeem Ullah and later with Seon Gu Kim as a project leader. Several people at STRI have contributed to the work.

Comments on the work and the final report have been given by a reference group with the following members:

| | |
|---|---|
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| Nikkilä Antti-Juhani | Fingrid |
| Terje Gjengedal, | Statnett |
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# Sammanfattning

Vid studier av tillförlitlig drift av moderna och större, sammanlänkade kraftsystem, kan man se att ett område som skapar bekymmer är svagt dämpade effektpendlingar i området 0,1 – 0,8 Hz. Bland annat kan reglersystemet för styrning av spänning och reaktiv effekt inom en vindkraftspark känna av dessa svagt dämpade effektpendlingar, vilket kan resultera i likaledes varierande utmatning av reaktiv effekt från vindkraftverken. I ett värsta scenario finns risken att reglersystemet förstärker effektpendlingen i kraftsystemet vid en specifik frekvens.

Denna rapport beskriver resultat från analyser av interaktionen mellan en spänningsregulator i en vindkraftspark och det sammanlänkade nordiska elkraftsystemet vid en effektpendling som berör hela kraftsystemet. En spänningsregulator för en vindturbin från leverantören GE har använts för att studera dess dynamik vid störning i nätet med spänningsfall som följd. Olika placering av vindkraftparken i IEEE:s Two-Area System har analyserats. Man har även studerat påverkan på kraftsystemet vid uppförande av ett flertal planerade vindkraftsparker. Vid dessa studier har man använt sig av en modifierad modell av Nordic-32. Spänningsregulatorn är modellerad baserad på de av leverantören specificerade standarddata. Utöver dessa data har även andra parametervärden beaktats.

Studieresultaten visar att regulatorn kan hantera en frekvensförändring på 0,1 Hz på ett godtagbart sätt. Den typ av spänningsregulator som har använts i studien visar på en hög förstärkning vid 0,35 Hz. Genom att justera olika parametrar i spänningsregulatorn har dess förmåga att undertrycka spänningsstörningar förbättrats, men samtidigt påverkar dessa justeringar regulatorns stigtid negativt.

I de fall där IEEE:s Two-Area System har använts kan slutsatsen dras att påverkan är liten från vindkraftparker som är kopplade till kraftsystemets sändande och mottagande ände, så länge lastflödet hålls konstant. Vid sådan placering av parkerna påverkar regulatorns parameterinställning dämpningen endast marginellt.

Då vindkraftparken placeras närmare kraftsystemets huvudledning blir resultatet att effektpendlingarna ökar. Med en sådan placering ökar också påverkan av eventuell justering av regulatorns parametervärden.

Vid modellering och analys av ny vindkraftsproduktion i systemet, kommer påverkan på eventuella effektpendlingar dels att bero på spännings-regleringen i vindkraftsparkerna, men också av den förändrade lastflödet.

Vid de fall där man studerat det nordiska systemet med inkoppling av planerade vindkraftparker i Finland, så är endast denna åtgärd generellt sett positiv för hela systemet, speciellt vid fall med 0,35 Hz. När den producerade kraften överförs till Sverige sker en negativ dämpning av systemet. Den observerade dämpningen kan inte endast tillskrivas regulatorerna, utan är en följd av den utökade lastflödet i ledningarna.

När hela den planerade vindkraftgenereringen appliceras i modellen, kommer dämpningen av eventuella effektpendlingar att förbättras i jämförelse med fall utan någon vindkraft. Återigen kan det nämnas att denna förbättring kan bero på skillnaden i kraftgenereringen och lastuttaget i de olika studerade fallen.

Resultaten visar även att det har en mindre påverkan på systemets dynamik när man ändrar parametervärden i spänningsregulatorn från standardvärden till värden där kravet på en stigningstid på 1,0 sekunder innehålls.

# Summary

Among the power system stability phenomena, poorly damped inter-area oscillations in the range of 0.1Hz to 0.8Hz are a concern for a reliable operation of modern large interconnected power systems. The poorly damped oscillations might be sensed by the voltage/reactive power controllers within wind farm and could be reflected on the output of the wind farm in the form of varying reactive power. In a certain worst case, the wind farm controller output may exhibit oscillatory behaviour at a certain frequency and thus oscillatory reactive power injection from wind farms might degrade the damping of the existing inter-area electromechanical oscillations.

This report deals with the investigation of the effect of wind farm (WF) voltage controller on inter-area power oscillations in the Nordic interconnected power system. In this regard, a voltage disturbance rejection capability of a GE wind turbine based WF voltage controller is analyzed. The effect of the location of a WF with voltage controller is analyzed for an IEEE two-area test system. The effect of several planned WFs is analyzed on a modified Nordic-32 test system. The manufacturer specified default values of the voltage controllers are used in the study. In addition, other values of the voltage controller parameters are also considered.

From the studied case considered, it is found that a 0.1 Hz change in frequency is quite effectively rejected by the controller. The particular WF voltage controller exhibits a high gain at 0.35 Hz. The gain and phase characteristics of the voltage disturbance rejection capability of the voltage controller at 0.35 Hz have been adjusted by varying different voltage controller parameters which will also affect the rise time of the voltage controller.

From the cases studied in the IEEE two-area test system, it is concluded that the impact of WFs connected close to the sending or receiving end is small as long as the power flow through the tie line is not impacted. The parameters of the voltage controller have only small influence on the damping for these locations.

A WF connected close to the tie line, results in a higher level of inter-area oscillations. For these locations, the impact of the parameters of the voltage controller is bigger.

When the incoming wind power is accommodated by changing the area and/or system load/generation, then the impact on the inter-area oscillations is a combination of the impact of the voltage controller and the changed load flow.

From the case studied in the Nordic system, it is found that the sole impact of the planned WFs' voltage controllers in Finland (FI), on the 0.35 Hz mode, is in general positive. When the production from WFs is exported to Sweden (SE) increasing the tie line flow, the mode becomes negatively damped. The observed negative damping of the 0.35 Hz mode cannot be attributed to the WF voltage controllers, instead it is a ramification of the increased tie line flow.

When all the planned WFs are included, it is found that the damping of the inter-area mode is improved compared to the case where no wind power was

considered. Again, the improvement of the damping can be due to the changed system load flow and generation dispatch conditions considered.

Changing, in the model of the Nordic system, the settings of the voltage controller from the GE default values to values that comply with the 1-second rise-time requirement has only minor impact on the results.

# Contents

# 1 Introduction

## 1.1 Background and aim of the project

One of the political aims in Sweden is to develop a third pillar for electricity supply to reduce vulnerability and increase security of electricity supply by reducing the dependence on nuclear and hydro power plants [11]. Wind power will be a vital component of this third pillar of electricity supply in Sweden. To be able to achieve a target of 30 TWh of wind energy production by 2020 – one of the key points in the energy agreement – about 8500 MW of new wind capacity (beyond the almost 3000 MW installed end of 2011) needs to be installed, assuming 30% capacity factor from wind farms. Other Nordic countries also have ambitious renewable energy source (RES) integration target. This will represent a significant share of wind power in the future generation mix of Nordic countries.

From a power system point of view, total understanding of technical impacts of this new generation source on the existing power system is vital to ensure a secure and reliable operation of the power system. Generators employed in conventional power plants are synchronous machines with round rotors or salient pole rotors - the modelling, operation and control of which are well understood [1]. In addition, there are also well published operational and control related system experiences involving these types of machines.

In a higher wind power penetration scenario, wind power plants will need to contribute to system voltage and frequency control support, which is quite obvious and logical. In fact several system operators already place such demands on wind power plants. The Swedish transmission system operator (TSO) Svenska Kraftnät (SvK), together with other Nordic and European TSOs is in the process of publishing updated sets of grid codes for wind power plants.

As has been mentioned earlier, several TSO/ISOs have issued or are in the process of issuing requirements regarding contribution to control of system voltage magnitude from wind farms. The voltage controller of a wind farm is typically in the form of a PI controller [12]. Among the power system stability phenomena, poorly damped inter-area oscillations in the range of 0.1 Hz to 0.8 Hz are a concern for a reliable operation of modern large interconnected power systems. Existing poorly damped oscillations in voltage magnitude and angle will be sensed by wind farm voltage/reactive power controllers and could be reflected on the output of the wind farm in the form of varying reactive power with phase angle shift compared to the oscillations in voltage magnitude, determined by the wind farm controller characteristics. Such reactive power oscillations from wind farms – induced from the existing power system phenomena – may, in the worst case, degrade the damping of the existing inter-area electromechanical oscillations l.

Some of the concerns for a power system planner in this regard are:

1. Among the power system stability phenomena, poorly damped inter-area oscillations in the range of 0.1 Hz to 0.8 Hz are a concern for a reliable operation of modern large interconnected power systems. Will reactive power oscillations from wind farms voltage controllers adversely affect this stability phenomenon?
2. How should the wind farms voltage controller parameters be tuned?
3. Will it be necessary to review the parameter tuning of power system stabilizers (PSS) of existing synchronous generators in the presence of wind farms voltage controllers?
4. Whether voltage oscillations introduced from wind farms will propagate through the system and impact the rotor angle or small-signal stability of existing synchronous generators?

## 1.2 Outline of the report

After this introductory chapter, the report is organized in the following way:

Chapter-2: Model used and cases studied are briefly mentioned in this chapter.

Chapter-3: Eigenvalue analysis and parameter sensitivity analysis of the wind farm voltage controller are presented in this chapter. The wind farm (WF) voltage controller grid voltage disturbance rejection capability is also analyzed in this section.

Chapter-4: A fundamental study of the impact of wind farm voltage controller on inter-area oscillations are carried out on an IEEE two-area system and the results are presented in this section. The purpose is to draw some generic conclusions.

Chapter-5: Several planned WFs are included into a modified Nordic-32 grid that represents the actual Nordic grid in terms of the inter-area mode. The expected impact of planned WFs is calculated in this chapter and the results are presented.

# 2 Models utilized and cases studied

## 2.1 Wind farm model

A manufacturer released model of a multi-MW commercially-available variable speed wind turbine (GE 3.6 MW) is used in this work. The model is adopted from [4]. This model is also included in the model library of PSSE as user written models, the description of which can be found in [5].

In the calculations, an aggregate model of WFs is used, i.e., many wind turbines (WT) of an actual WF are modelled as a single WT with appropriate voltage transformations connected at the point-of-connection (POC) of the grid. Further modelling details will be given in each section.

## 2.2 Network model

### 2.2.1 IEEE two-area system

An IEEE benchmark two-area system is used in some calculations. The model was originally presented in [6]. Later, a stressed version of the model was published in [7]. In our work, we have used the stressed version of the system. Further details of the model will be given in Chapter 4.

### 2.2.2 Modified Nordic-32 system

The original CIGRE Nordic-32 system is a representation of the Nordic interconnected power system intended to study voltage instability phenomena in the system [8]. We have augmented the test system to include the existing inter-area oscillations. The modifications made will be explained in more detail in later chapters.

## 2.3 Cases studied

### 2.3.1 Single machine case

In this case, a WF is connected to a grid represented by an ideal voltage source behind a reactance. This case is used to analyze the WF voltage controller performance under various grid conditions.

### 2.3.2 IEEE two-area case

In this case, a WF is connected to different locations of the IEEE two-area system. The purpose is to identify how WF locations in the grid affect the inter-area oscillations.

### 2.3.3 Wind farms in Finland case

In this case, some of the planned WFs in Finland are considered – network model used is the modified Nordic-32 grid. The purpose is to identify how planned WFs in Finland affect the inter-area oscillations. It is to be noted that the generators in Finland have high participations in one of the critical inter-area modes in the Nordic interconnected system. Therefore the planned WFs in Finland are studied separately.

### 2.3.4 Wind farms in Nordic case

In this case, planned WFs in Norway (NO), Sweden (SE) and Finland (FI) are considered. Two different cases are studies both with high export from FI to SE. The cases will be discussed in more detail in later chapters.

## 2.4 Study approach

As has been mentioned earlier, the purpose of this project is to investigate how the WF voltage controllers will influence the existing inter-area oscillations in the Nordic grid. To be able to do so, we have taken the following approach:

- First we have analyzed the small-signal characteristics of the WF voltage controller. A linearized model of the controller has been developed for this. The voltage controller's eigenvalues have been calculated using the GE default controller values. Later, the sensitivities of eigenvalues on different parameter changes are calculated.
- The forced vibration characteristics of the voltage controller are calculated. By forced vibration characteristic, we mean how a disturbance of grid voltage at the point of connection (POC) is sensed by the WF and how the WF alters its reactive power injection to counterbalance the voltage oscillations. When a WF is located in an area of the grid where there exists underdamped low frequency oscillation in the voltage magnitude, under such circumstances WF disturbance rejection capability is important to be studied.
- A single WF is connected at different buses (sending end, receiving end, on tie line) of the IEEE two-area system. In this case we have considered that the WF active power is at the minimum level and that minimum power is consumed locally, i.e., no active power is injected into the grid. In this way, the network power flow is not impacted by the presence of the WF. The only difference the connection of WF thus makes is the presence of WF voltage controller. In this way we will be able to gain an insight into the mechanism by which WF voltage controllers influence the damping of inter-area oscillations. Later, full production scenario from WF will be considered, but the tie line flow will be kept unchanged. Different values of the voltage controller parameters will be considered – GE default values and other values resulting in a 1 sec rise time from the voltage controller.

- Planned WFs in FI will be considered next and the network used will be the updated Nordic-32 grid. Generators in FI have high participation in a 0.35 Hz inter-area mode which is considered critical in the system because low damping of this mode sometimes limits the secure transfer capacity of the tie lines. That's why the planned WFs in FI are treated separately. Again in this case we start with a minimum wind power production from WFs and that minimum power is consumed locally so that no power is injected into the grid. In this way we will be able to assess the sole impact of WF voltage controller on the inter-area mode. The damping of inter-area mode depends on the power flow in tie lines, location of generators with PSS and loads in the systems and their voltage dependency, among others [1]. Introduction of wind power into the grid will cause significant change in the power flow compared to a no-wind scenario. However, such two scenarios cannot be used for the basis of a comparison and assessment of WF voltage controller's impact on inter-area mode. That's why we will use the minimum wind power scenario extensively in this work. Later we will also calculate the small-signal property of the system taking full wind power production and the resulting load flow changes into account. Different values of the voltage controller parameters will be considered – GE default values and other values resulting in a 1sec rise time from the voltage controller
- Planned WF in NO, SE and FI will be considered together. Two different balance cases will be studied both with export from FI to SE.

## 2.5 Software used

The following modules of PSSE have been used in the calculations: load flow, dynamic, LSYSAN. Matlab has also been used for some of the calculations.

# 3 Analysis of the wind farm voltage controller

## 3.1 GE wind farm voltage controller

The example wind turbine system reactive power and voltage control scheme is shown in Figure 3.1. It consists of three levels of control namely, a very fast WT terminal voltage control, followed by a relatively slow WT reactive power control and a slow supervisory plant level voltage controller which is a PI type controller. The default values of the controller parameters are shown in [5].

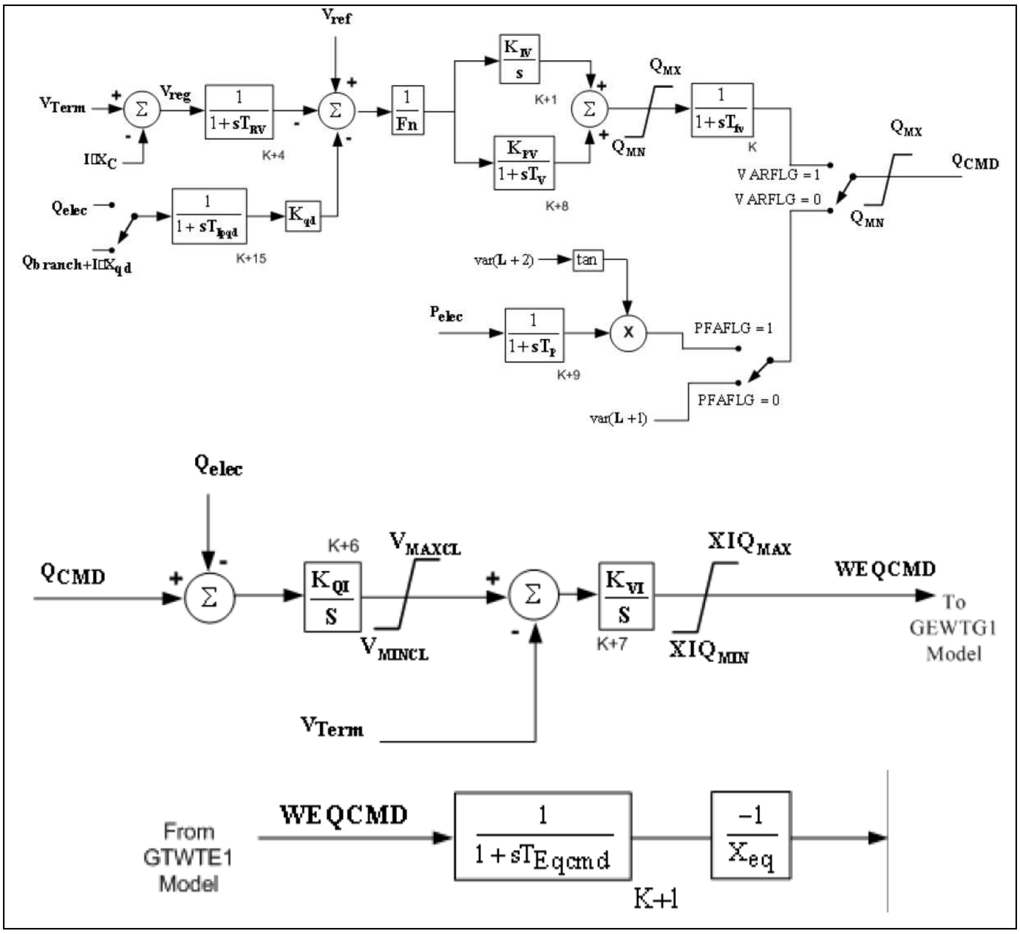


Figure 3.1: WT voltage and reactive power control scheme, redrawn from [5].

Three controll parameters (i.e. Kpv, Kiv, KQi) within PI voltage controller will be our main interest; Kpv is proportional constant Kpv, is integral constant and KOi is the proportional gain between voltage and reactive-power production.

The manufacturer specified recommended values for the PI voltage controller are 18 (proportional constant Kpv) and 5 (integral constant Kiv). The above mentioned PI controller parameter values gives better voltage response to grid voltage disturbance for systems with a short circuit of 5 or more times the WF rating [4]. The lowest values for the controller parameters are 2 and 1, respectively. The values of the parameter KQi can be set to 0.1 to 0.5 [4].

## 3.2 State-space model of the voltage controller

A linearized model of the voltage controller is shown in Figure 3.2.

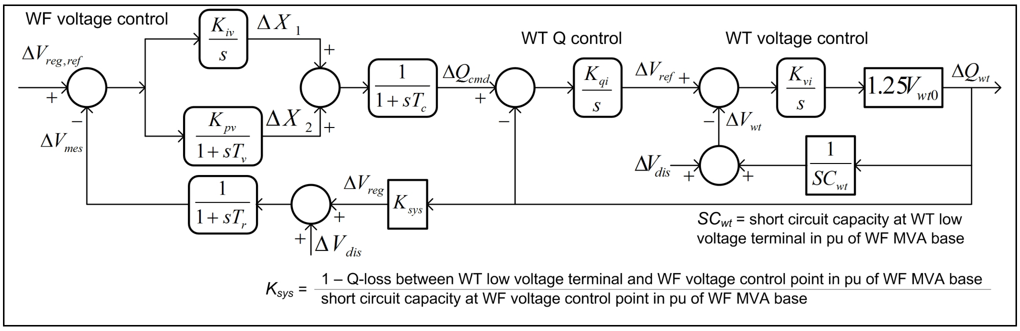


Figure 3.2 A linearized model of the voltage controller.

A dynamic system model is represnted by state space form for modal analysis as below.

$$\frac{\partial x(t)}{\partial t} = A \cdot x(t) + B \cdot u(t)$$
$$y(t) = C \cdot x(t) + D \cdot u(t)$$

The states chosen to represent the system are $\Delta X_1$, $\Delta X_2$, $\Delta Q_{cmd}$, $\Delta V_{ref}$, $\Delta Q_{wt}$ and $\Delta V_{mes}$ .

The plant matrix 'A' can be written as:

A=

| | $\Delta X_1$ | $\Delta X_2$ | $\Delta Q_{cmd}$ | $\Delta V_{ref}$ | $\Delta Q_{WT}$ | $\Delta V_{mes}$ |
|---|---|---|---|---|---|---|
| $\Delta \dot{X}_1$ | 0 | 0 | 0 | 0 | 0 | $-k_{iv}$ |
| $\Delta \dot{X}_2$ | 0 | $-\frac{1}{T_v}$ | 0 | 0 | 0 | $-\frac{k_{pv}}{T_v}$ |
| $\Delta \dot{Q}_{cmd}$ | $\frac{1}{T_c}$ | $\frac{1}{T_c}$ | $-\frac{1}{T_c}$ | 0 | 0 | 0 |
| $\Delta \dot{V}_{ref}$ | 0 | 0 | $K_{Qi}$ | 0 | $-K_{Qi}$ | 0 |
| $\Delta \dot{Q}_{WT}$ | 0 | 0 | 0 | $\frac{K_{Vi}}{0.8}$ | $-\frac{K_{Vi}}{0.8SC_{WT}}$ | 0 |
| $\Delta \dot{V}_{mes}$ | 0 | 0 | 0 | 0 | $\frac{K_{sys}}{T_r}$ | $-\frac{1}{T_r}$ |

The inputs are *$\Delta V_{reg,ref}$* and *$\Delta V_{dis}$*, accordingly the input matrix 'B' can be written as:

B=

$$
\begin{matrix}
K_{iv} & 0 \\
\frac{K_{pv}}{T_v} & 0 \\
0 & 0 \\
0 & 0 \\
0 & -\frac{K_{vi}}{0.8} \\
0 & \frac{1}{T_r}
\end{matrix}
$$

Outputs variable is ΔQwt and accordingly the output matrix 'C' is:

C=

$$
\begin{matrix} 0 & 0 & 0 & 0 & 1 & 0 \end{matrix}
$$

### 3.2.1 Eigenvalues

The default values of the WF voltage controller give satisfactory results for grid strength equal to or above 5 times the WF capacity [4]. Using these default values, the dominant eigenvalues calculated are: -1.74 +/- j5, -0.23.

There are also three other eigenvalues with very large negative values which will not have significant influence on the dynamic performance of the controller as they will die out very fast.

### 3.2.2 Parameter sensitivity analysis

The sensitivity of the dominant eigenvalues of the WF voltage controller as affected by various grid and control parameters are calculated. The parameters varied are: grid strength, *Kiv*, *Kpv*, *KQi* and PI controller gain. In all cases the starting point of the controller parameters and grid strength are the GE default values. Different parameters are varied one at a time to be able to identify the movement of the dominant eigenvalues caused by the variation of this particular parameter. Dominant eigenvalues calculated using the default values are always marked with 'x' in the following figures.

Varying grid short circuit capacity:
As has been mentioned earlier, GE default values for the WF voltage controllers give satisfactory results when the grid short circuit capacity is at least 5 times higher than the WF rated capacity. In this case we have changed the grid short circuit capacity in both directions from the design value while keeping the controller parameters at the default values. Dominant eigenvalues movements are shown in Figure 3.3. As can be seen from the figure the real eigenvalues are not so sensitive to grid strength changes. However, the complex eigenvalues show high sensitivity. It can be concluded that when the grid strength reduces, the WF voltage controller response will be more oscillatory and less damped.

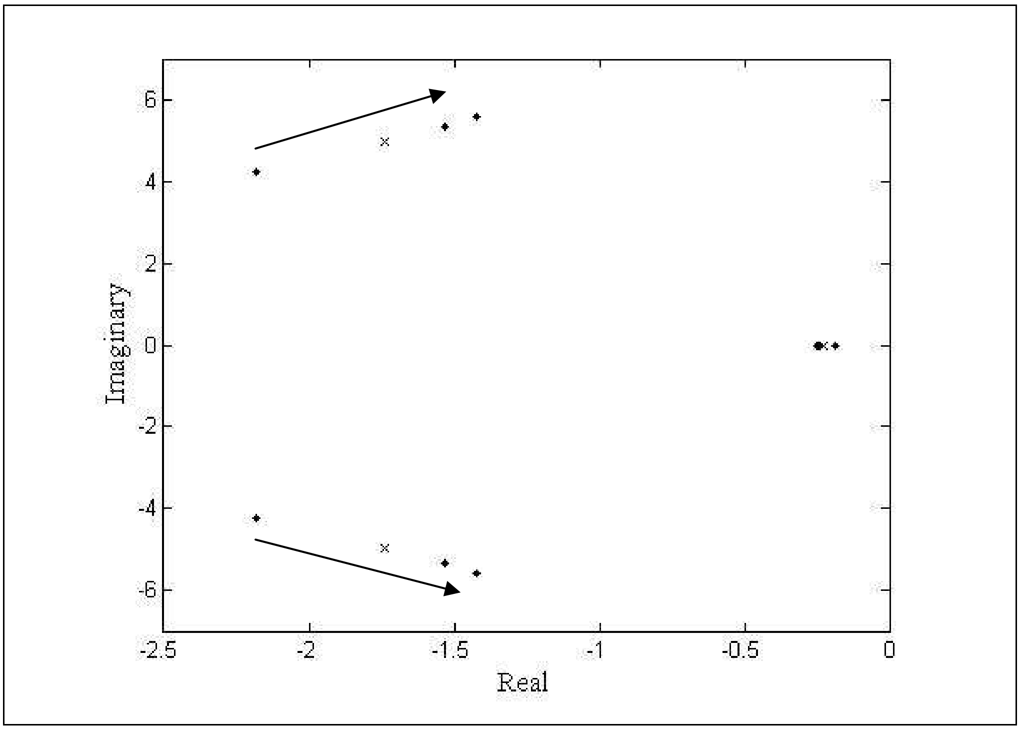


Figure 3.3 Dominant eigenvalues of the WF voltage controller as calculated from the plant matrix 'A'. Grid impedance varies from 0.1 to 0.4 with 'x' represents 0.2 (values are in pu of WF rated MVA, i.e., a value of 0.1 means

the grid short circuit capacity is 10 times higher than the WF rated capacity). The arrow indicates the movement of the eigenvalue with increasing grid impedance.

Varying Kiv:
The complex eigenvalues pair has less sensitivity towards *Kiv* changes, while the real eigenvalue moves towards the imaginary axis when Kiv is reduced, as can be seen from Figure 3.4. The effect of this is that the residue associated with this pole will decay slowly when Kiv is reduced.

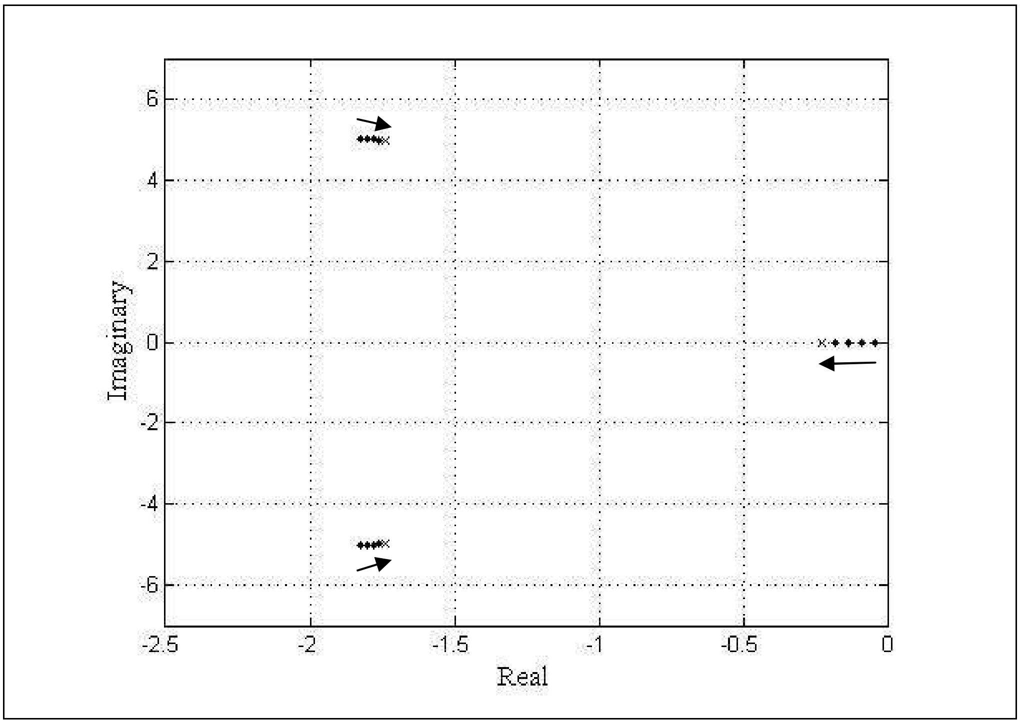


Figure 3.4 Kiv varies from 1 to 5 with 'x' represents 5. The arrow indicates the movement of the eigenvalue with increasing Kiv.

Varying Kpv:
When the values of Kpv are varied from 18 to 2, the complex poles move towards the real axis meaning a less damped response, while the real pole moves away from the imaginary axis. At Kpv=4, one of the complex poles moves further away from the imaginary axis to become a real pole and the other one combines with the other real pole to become a complex pole. Please see Figure 3.5.

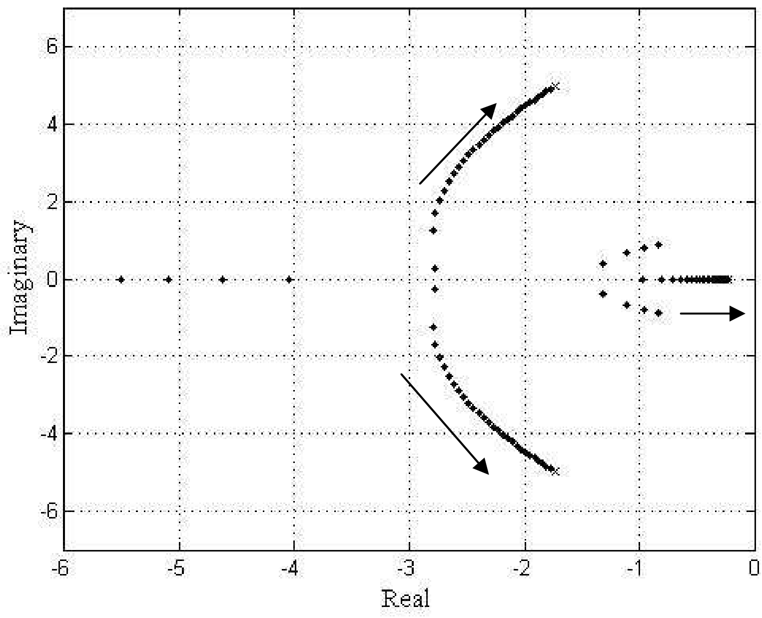


Figure 3.5 Kpv varies from 2 to 18 with 'x' represents 18. The arrow indicates the movement of the eigenvalue with increasing Kpv.

<u>Varying KQi:</u>
The real pole is relatively insensitive towards changes in KQi. But the complex pole is quite sensitive. As can be seen from Figure 3.6, the voltage controller response will become less oscillatory and well damped when KQi value is reduced.

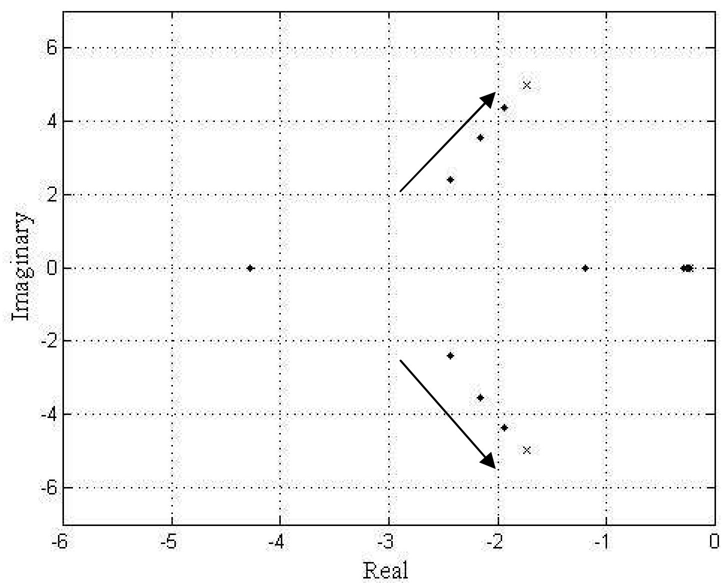


Figure 3.6 KQi varies from 0.1 to 0.5 with 'x' represents 0.5. The arrow indicated the movement of the eigenvalue with increasing KQi.

Varying PI controller gain:
The complex pole becomes more oscillatory and less damped when PI controller gain is increased, please see Figure 3.7. The real pole is relatively insensitive towards any change in PI controller gain.

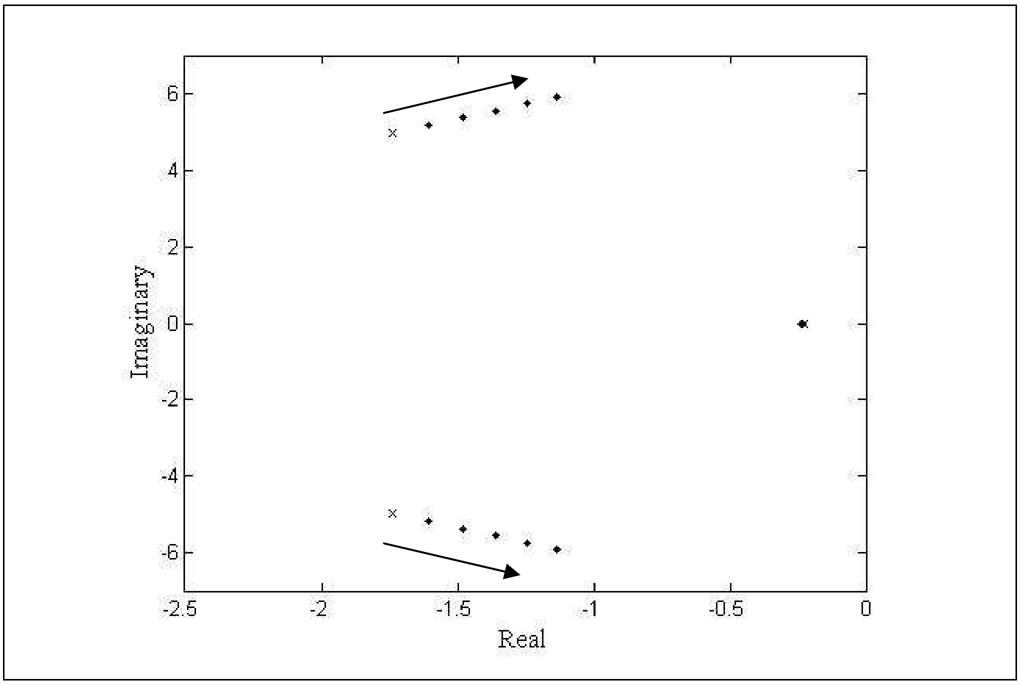


Figure 3.7 Gain varies from 1 to 1.5 with 'x' represents 1. The arrow indicates the movement of the eigenvalue with increasing gain.

The findings are summarized below:

1. Response becomes more oscillatory and less damped when grid strength is reduced.
2. When Kiv is reduced, the response associated with the real pole becomes slower.
3. When Kpv is reduced, the response becomes less oscillatory and better damped.
4. When KQi is reduced, the response becomes less oscillatory and better damped.
5. When the gain of the PI controller is increased, the response becomes more oscillatory and less damped.

## 3.3 Disturbance rejection capability of the voltage controller

To calculate the disturbance rejection capability of the WF voltage controller, we will examine the transfer function from $\Delta V_{dis}$ to $\Delta Q_{wt}$. The WF voltage controller works in this way: The purpose of the WF voltage controller is to control the voltage at a certain bus within the WF installation, usually at the POC. When the reference voltage set point is changed, the WF voltage controller calculates the necessary reactive power needed to change the controlled bus voltage and sends the command to WTs within the WF. The WTs then increase or decrease the reactive power production from them. The process is a feedback control process. How fast or slow the controlled bus voltage will attain the new set value will depend on the voltage controller gain and phase characteristics.

Usually, a controller is designed to achieve a certain response time characteristic. For example, a WF voltage controller will be designed so that when the set point voltage is changed in a step, the response from the WF is non-oscillatory or oscillatory but well damped.

However, if there is any sustained low frequency oscillation in the grid voltage magnitude while the WF set point voltage remains the same, the response from WF reactive power injection will be quite different. In this case the response will be to counterbalance the grid voltage disturbances. The phase and gain characteristics will depend on the disturbing frequency and the WF voltage controller.

The transfer function from $\Delta V_{dis}$ to $\Delta Q_{wt}$ will reveal the disturbance rejection capability of the controller which can give us useful insight into the mechanism by which the controller will influence the existing inter-area oscillation at the grid.

The sensitivity of the disturbance rejection capability of the WF towards changes in different controller parameters is also calculated. The purpose is to calculate the frequency response of the WF around 0.35 to 0.4 Hz. In the Nordic interconnected system, the generators in FI oscillate against generators in south of SE and NO at around 0.35 Hz. So, the planned WFs in FI will experience voltage magnitude variations at this frequency range. In the following frequency response plots, diagrams with dots (.) always represent the frequency response of the WF voltage controller with GE specified default values and for a system with short circuit capacity of 5 times the WF rated capacity.

Figure 3.8 shows the disturbance rejection capability of the WF voltage controller. As can be seen from the figure with dots (.), a 0.1 Hz change in frequency is quite effectively rejected by the controller up to 0.1Hz (phase angle remains close to 180 degrees). At frequencies higher than that, the lead angle becomes less than 180 degree. At around 0.35 Hz (2.2 rad/sec) the lead angle is around 160 degrees. As can be seen from the figure, the WF voltage controller exhibits a high gain at 0.35 Hz.

Figure 3.9 shows the disturbance rejection capability is relatively unaffected by changes in Kiv at 0.35 Hz.

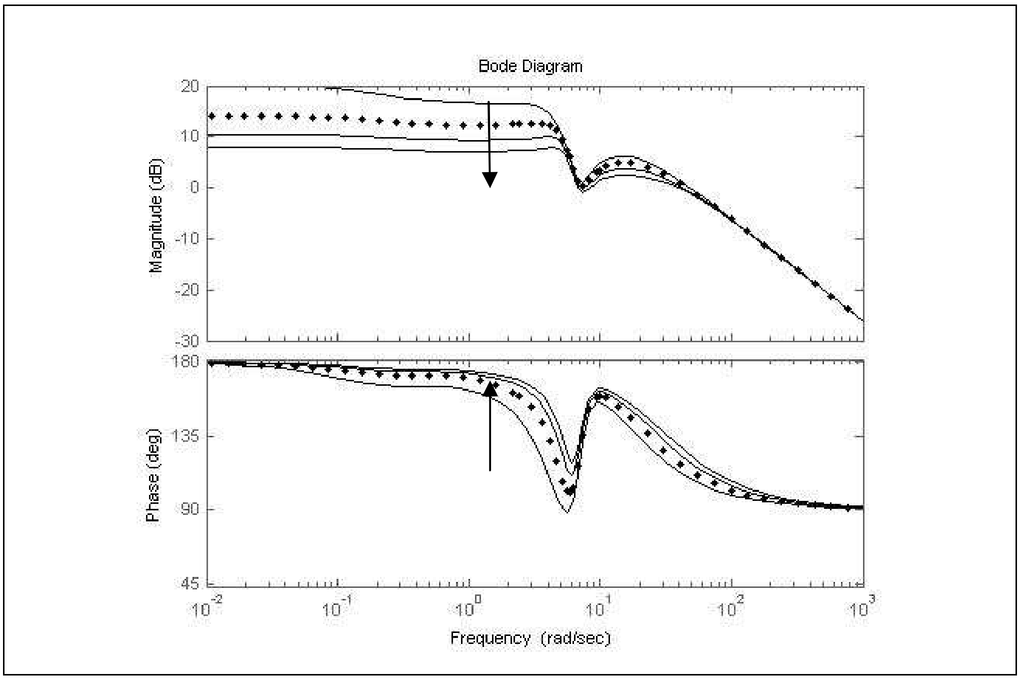


Figure 3.8 Disturbance rejection capability of the WF voltage controller. Controller parameters according to the GE guideline and grid strength is 5 times the WF rated capacity, grid strength varies from 0.1 to 0.4 with diagram with dots (.) represents grid strength 0.2. The arrow indicates the plot with increasing grid strength.

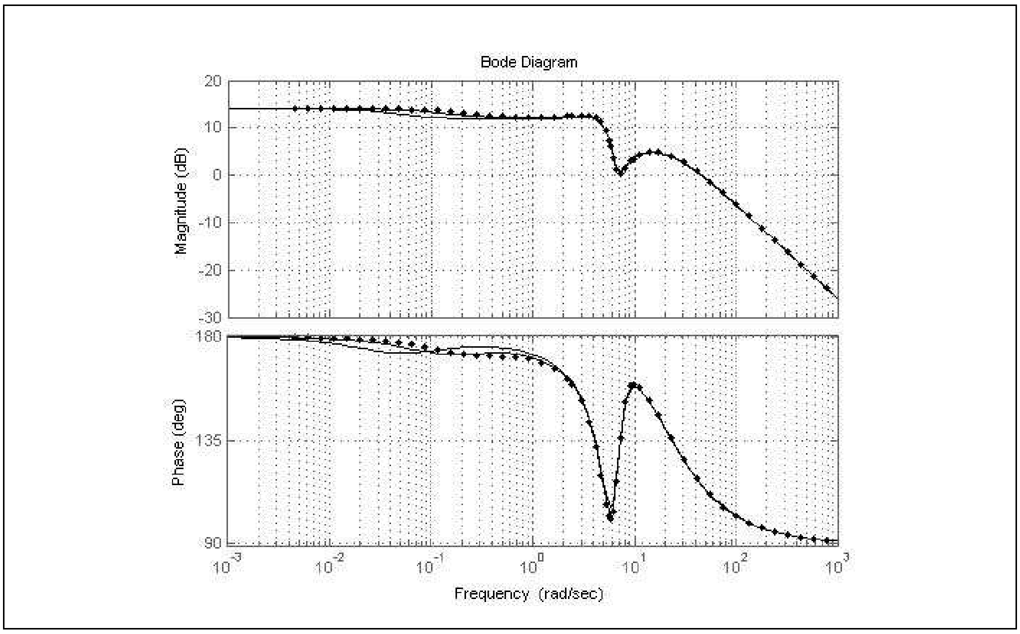


Figure 3.9 Frequency response by varying Kiv from 1 to 5 with diagram with dots (.) represents the value 5.

The sensitivity of the disturbance rejection capability to changes in Kpv is significant as can be seen from Figure 3.10. Both the gain and phase angle vary significantly at frequency 0.35 Hz. The effect of this on the step response is quite visible from the figure. Although the initial transient response remains the same, the subsequent response is much slower when Kpv values are reduced.

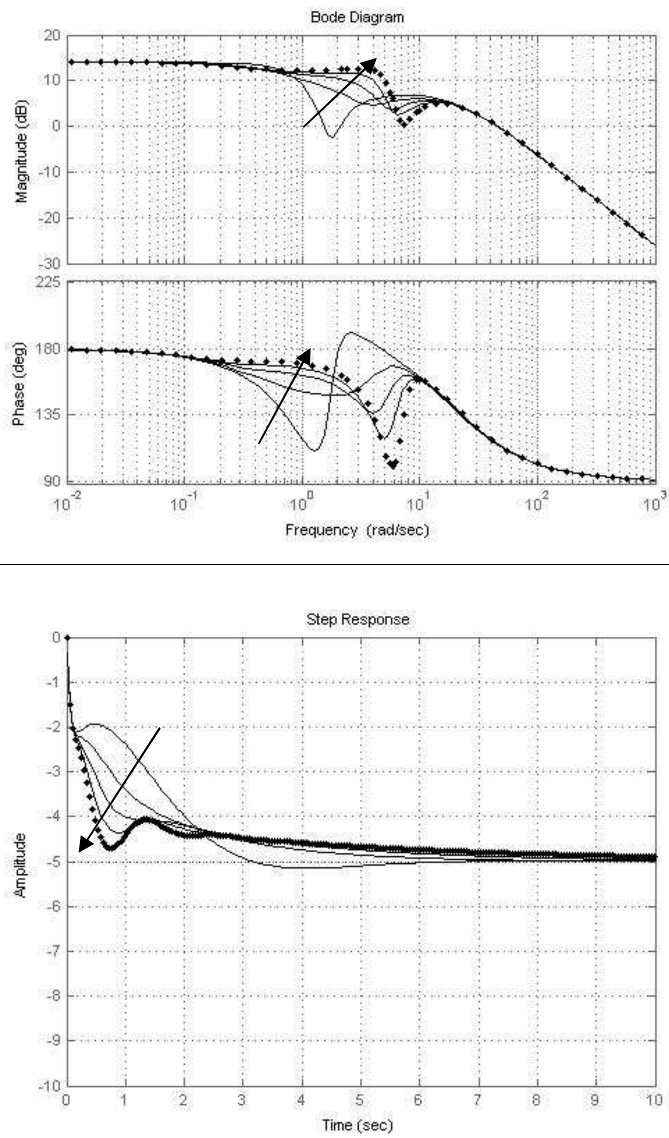


Figure 3.10 Kpv varies from 2 to 18 with diagram with dots (.) represents the value 18. Frequency (top) and step (bottom) responses.

The sensitivity of the disturbance rejection capability to changes in KQi is also significant as can be seen from Figure 3.11. The gain varies significantly at frequency 0.35 Hz while the variation of phase angle is relatively moderate. The effect of this on the step response is quite visible from the figure. Although the initial transient response remains the same but the subsequent response is quite slower when KQi values are reduced.

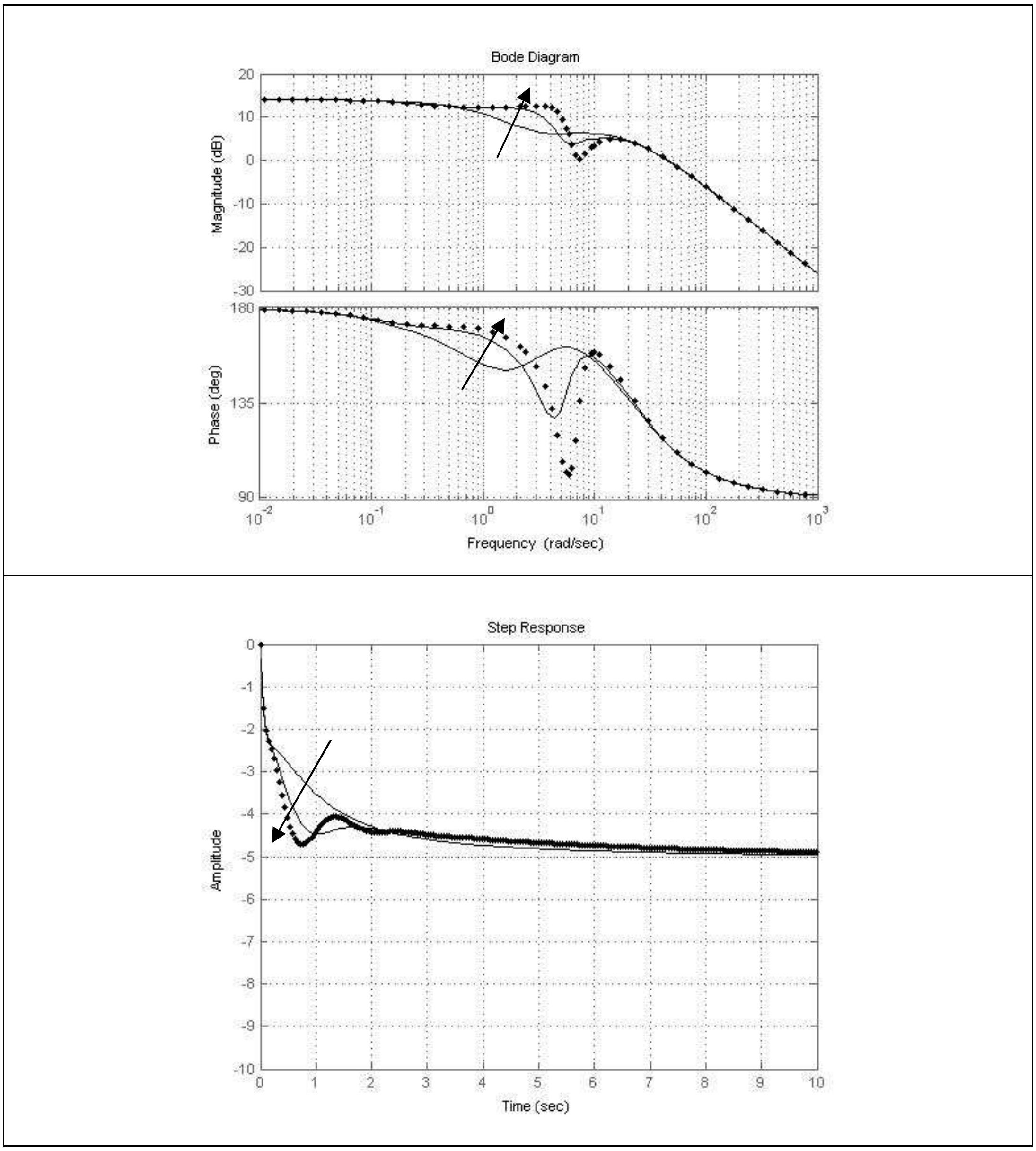


Figure 3.11 KQi varies from 0.1 to 0.5 with diagram with dots (.) represents 0.5. Frequency (top) and step (bottom) responses.

The sensitivity of the disturbance rejection capability to changes in PI controller gain is not so significant as can be seen from Figure 3.12. The variation in gain and phase angle is not so significant at frequency 0.35 Hz.

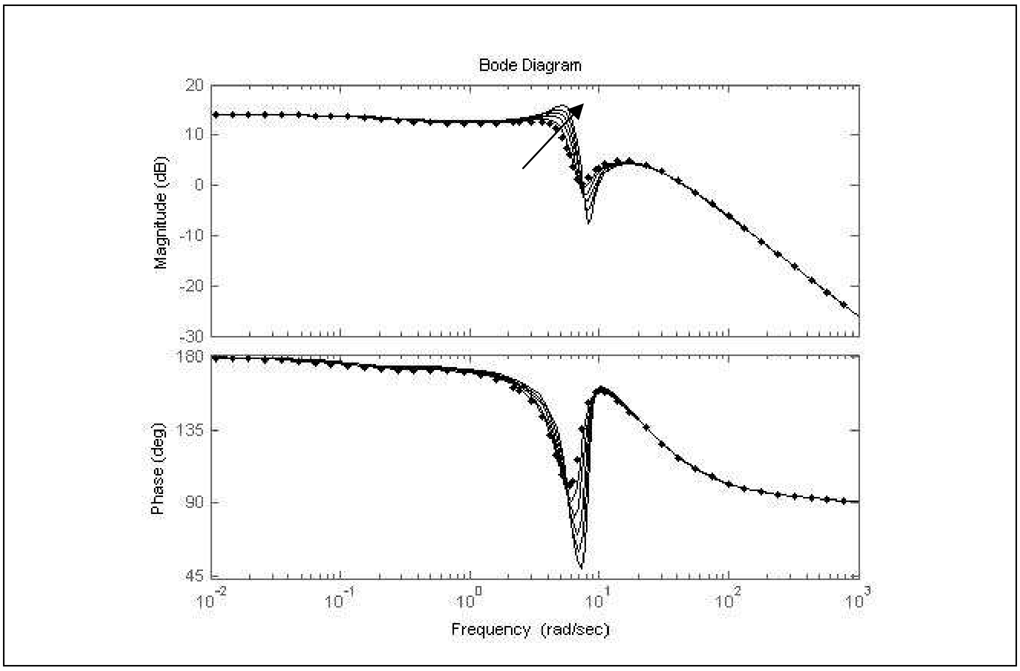


Figure 3.12 PI controller gain varies from 1.0 to 1.5 with diagram with dots (.) represents 1.0. Frequency (top) and phase (bottom) responses.

# 4 A fundamental study on inter-area power oscillations as affected by wind farm voltage controllers

## 4.1 Description and characteristics of the system studied

The IEEE benchmark two-area system used in this chapter is shown in Figure 4.1. The model was originally presented in [6]. Later, a stressed version of the model was published in [7]. In our work, we have used the stressed version of the system. The transfer from area-1 to area-2 is 400MW over a single tie circuit of 220km. System parameters are given in [7]. Generating units are loaded with 700 MW each and the area 1 and 2 loads are 970 and 1770 MW, respectively.

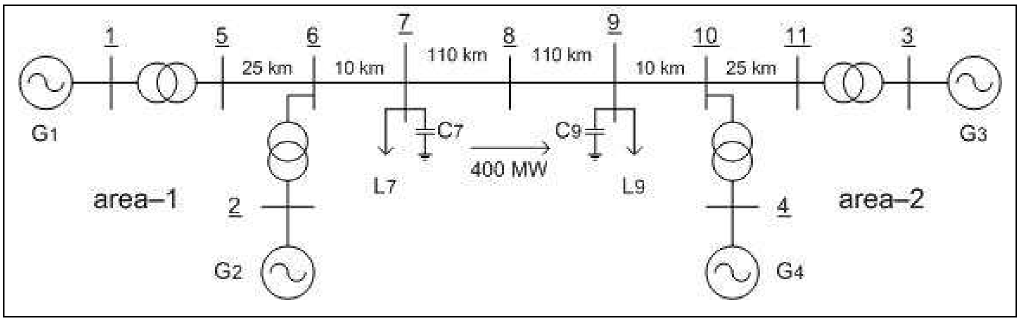


Figure 4.1 The used IEEE two-area system.

From linear analysis using PSSE LSYSAN, the system inter-area mode is calculated as 0.37 Hz and the damping constant is 6.8%. In this mode of oscillation, generators in area-1 oscillates against generators in area-2. The participation factors and the magnitude of eigenvectors are shown in Figure 4.2.

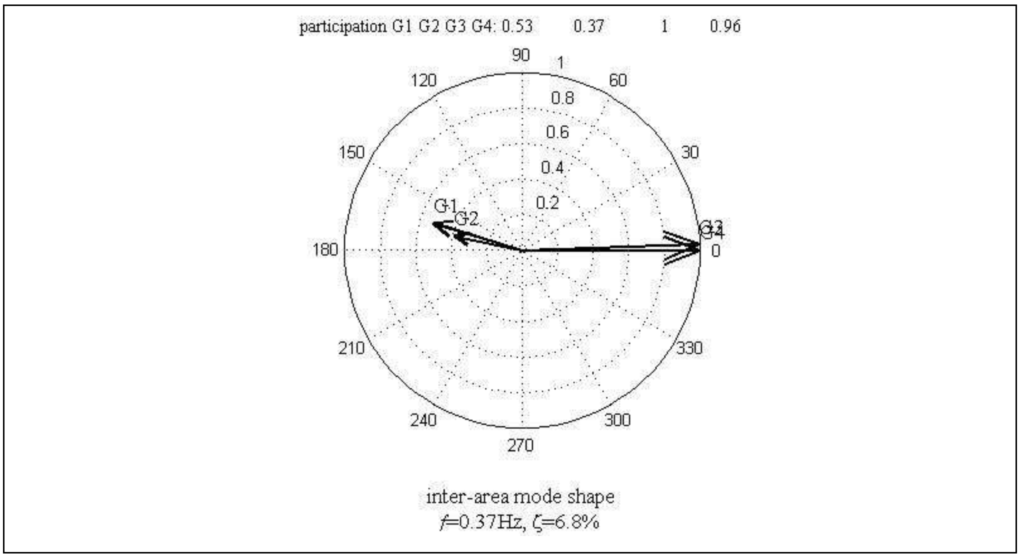


Figure 4.2 0.37Hz mode shape.

As has been mentioned earlier, the Nordic interconnected system exhibits an inter-area mode of oscillation at 0.35 Hz and at this frequency generators in south of FI oscillate against generators in south of NO and south of SE. The damping of this mode is quite low which sometimes limits the safe transfer limit of different interconnections [9].

The reason for using the stressed version of the IEEE two-area system is the similarity of the frequency of the inter-area mode with that of the Nordic system. Another reason is that the test system has extensively been used in research and the conclusions drawn from the original study are still valid. So the results from our work on this system can be generalized and can be used in other work.

## 4.2 Study procedure

The WF layout studied in this section is shown in Figure 4.3. The WF voltage controller controls the voltage at the HV side of the last step-up transformer. The WF rated capacity is 600 MVA and its maximum active power production is limited to 540 MW. The WF voltage controller parameters used are both the GE specified default values and non-default values that result in a 1sec rise time from the WF voltage controller.

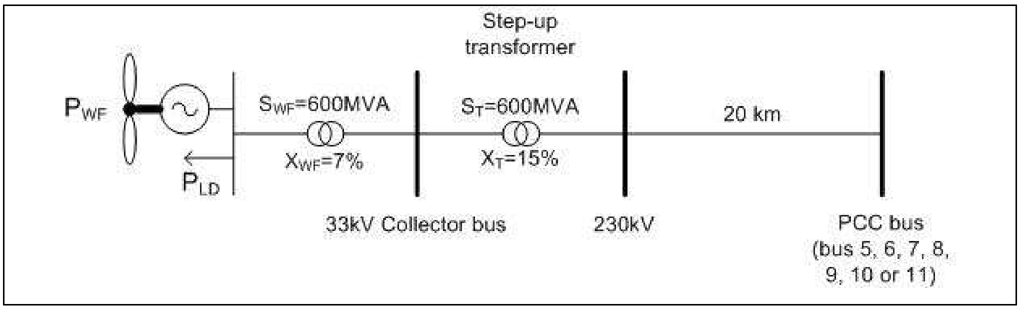


Figure 4.3 WF layout studied.

In the subsequent analysis, we will consider a minimum wind power production from the WF and that minimum power will be consumed locally. In this way the WF will not inject any active power into the transmission grid while connected. The WF will then be connected at bus 7 through 11 sequentially and the results will be analyzed. While repeating this process, we will not change any of the system conditions of the IEEE system, i.e., the tie-line transfer will be kept at 400 MW from area-1 to area-2. The only difference the WF will bring on this system is that during disturbances, the system will experience a new dynamic reactive power source acting on it. The purpose of doing this is to identify the sole impact of the WF voltage controller on the inter-area mode. In this analysis we will consider two types of load characteristic – constant current load and constant power load. The WF voltage controller parameters used are both the GE specified default values and non-default values that results in a 1s rise time from the WF voltage controller

Later, a full production from the WF will be considered while keeping the tie-line transfer at the original 400 MW. The incoming wind power will be accomodated either by increasing the load or by decreasing the generation from other conventional generators. We will also consider another case where the incoming wind power will be accomodated by taking one conventional generator out of service and adjusting the load so that the tie-line transfer remains the same, 400 MW.

## 4.3 Sole impact of the wind farm voltage controller

### 4.3.1 Load characteristic and location of wind farms

The frequency and damping of the inter-area oscillation of the IEEE test system is calculated using both a constant current load and a constant power load. The results are shown in Table 4.1. In these calculations, the GE default values of the voltage controller are used. When a constant power load model is used, the damping of the inter-area mode is reduced compared to a constant current model as the effectiveness of the PSS in modulating system load is reduced [6]. The frequency and damping of the inter-area mode are calculated with varying locations of the WF. The results are also shown in Table 4.1.

Table 4.1: Frequency and damping constant of inter-area oscillation (GE default control values)

| Single WF location | Load characteristics | |
|---|---|---|
| | Constant current (f, ζ) | Constant power (f, ζ) |
| *No WF* | *0.37 Hz, 6.8%* | *0.35 Hz, 2.3%* |
| @BUS 5 *sending end* | 0.38 Hz, 7.2% | 0.35 Hz, 2.8% |
| @BUS 6 –''- | 0.39 Hz, 7.2% | 0.36 Hz, 2.5% |
| @BUS 7 –''- | 0.40 Hz, 6.5% | 0.37 Hz, 2.2% |
| @BUS 8 ***middle of tie*** | 0.43 Hz, 5.0% | 0.43 Hz, 0.8% |
| @BUS 9 *receiving end* | 0.37 Hz, 5.7% | 0.38 Hz, 1.9% |
| @BUS 10 –''- | 0.38 Hz, 5.7% | 0.36 Hz, 2.6% |
| @BUS 11 –''- | 0.38 Hz, 6.7% | 0.34 Hz, 2.7% |

An important conclusion from these studies is that the impact is strongly location dependent. The same controller can improve the situation at one location and deteriorate the situation at another location. This means that it is not enough to look at the controller only, but that the whole system needs to be considered.

A preliminary conclusion, for this controller in this system, would be that locations close to the generators give a small improvement, whereas locations close to the tie-line deteriorate the situation. The difference between sending and receiving end is small.

The maximum improvement in the damping of the inter-area mode in the presence of the considered WF voltage controller is around 0.4% when the WF is at the periphery of the sending end.

However, when the studied WF is located close to the load (bus 7) at the sending end, the damping of the inter-area mode is slightly reduced irrespective of the load characteristic. The reduction of the damping is larger when the load characteristic is voltage dependent.

The studied WF at the receiving end reduces the damping of the inter-area mode. The reduction is minimum when the WF is at the periphery of the receiving end. This fact is valid when the system load is voltage dependent.

However, when the load is voltage independent, the studied WF voltage controller improves the inter-area mode even when it is at the receiving end.

But, when the studied WF is located at the middle of the tie line, the damping of the inter-area mode is always reduced irrespective of the load characteristics.

To summarize, when the system load is voltage independent, the studied WF voltage controller may increase the damping of the inter-area mode if it is not located at the middle of the tie line or close to the load centres-no matter whether it is at the sending end or at the receiving end. However, when the load is voltage dependent, location may matter-the studied WF at the sending end close to the conventional generators and away from load centres may improve the damping of the inter-area mode. But when it is at the receiving end or at the middle of the tie line, damping of the inter-area may reduce. When WF is at the periphery of the receiving end, the impact of the voltage controller on the inter-area mode is almost negligible.

### 4.3.2 Voltage controller parameters variation

In the above analysis, we have only considered the GE default values of the WF voltage controller. In this section, we have considered other parameter combinations as shown in Table 4.2. Three locations of the WF are considered in this test – bus 5 sending end, bus 11, receiving end and bus 8 middle of tie line. Only the constant current load characteristic is considered.

Table 4.2: Wind farm voltage controller parameter combinations tested.

| | | Kiv | | |
|---|---|---|---|---|
| | | **1** | **3** | **5** |
| Kpv | **2** | 1. | 2. | 3. |
| | **6** | 4. | 5. | 6. |
| | **10** | 7. | 8. | 9. |
| | **14** | 10. | 11. | 12. |
| | **18** | 13. | 14. | 15. |

<u>WF @BUS 5 (sending end):</u>

The damping of the inter-area mode is calculated for few different WF voltage controller combinations. The results are shown in Table 4.3.

Table 4.3: damping of the inter-area mode for few selected voltage controller parameter combinations

| Voltage controller parameter combination | Damping of the inter-area mode |
|---|---|
| ***No WF*** | *6.8%* |
| **1.** | 7 .0% |
| **2.** | 6.9% |
| **3.** | 6.8% |
| **4.** | 6.9% |
| **11.** | 7.1% |
| **15.** | 7.2% |

Parameter combinations 4, 11 and 15 are interesting to note. At these parameter combinations, the wind farm voltage controller's forced vibration response from a disturbing voltage to the wind farm reactive power has a phase angle lead of around 160 degrees while the gain varies. And the effect of the increasing gain is an improvement of the damping of the inter-area mode. So we conclude that increasing the gain of the WF voltage controller located at the periphery of the sending end will slightly increase the damping of the inter-area mode. Overall however, the impact of the controller parameters is small.

Figure 4.4 shows the normalized right eigenvectors of generator rotor speed deviations (mode shapes) together with the wind farm reactive power deviation. It is noticed that, the WF reactive power deviation eigenvector lags the sending end generators speed deviations by around 35 degrees. The lag angle is reduced slightly when the gain is increased. It is noted that the WF voltage controller does not participate in the inter-area mode.

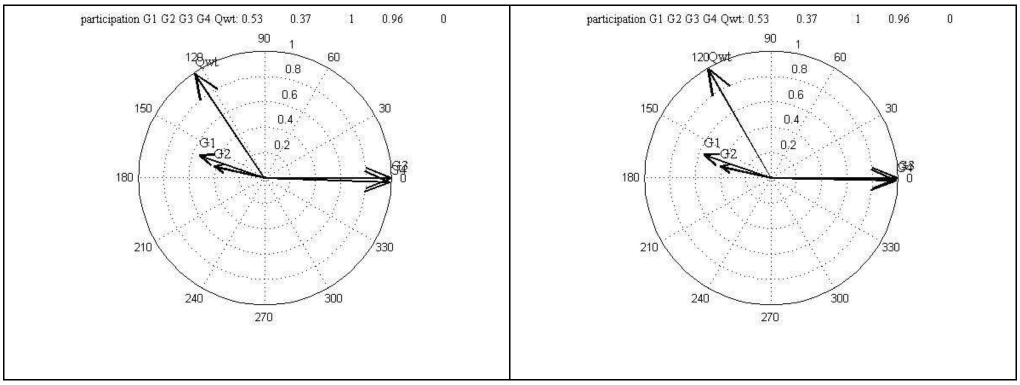

Figure 4.4 Normalized right eigenvectors of generators rotor speed deviations (mode shapes) together with WF reactive power power deviations corresponding to the inter-area mode. Corresponding participation factors are also printed. Parameter combination 4 (left) and 15 (right).

<u>WF @BUS 11 (receiving end):</u>

The damping of the inter-area mode is calculated for few different WF voltage controller combinations. The results are shown in Table 4.4.

Table 4.4: damping of the inter-area mode for few selected voltage controller parameter combinations

| Voltage controller parameter combination | Damping of the inter-area mode |
|---|---|
| ***No WF*** | *6.8%* |
| **1.** | 7 .0% |
| **2.** | 7.1% |
| **3.** | 7.1% |
| **4.** | 6.9% |
| **15.** | 6.7% |

We will again consider parameter combination 4 and 15. At these parameter combinations, the wind farm voltage controller's forced vibration response- from a disturbing voltage to the wind farm reactive power- has a phase angle of around 160 degrees while the gain varies. And the effect of the increasing gain is a slight decrement of the damping of the inter-area mode. So we conclude that increasing the gain of the WF voltage controller located at the periphery of the receiving end will slightly decrease the damping of the inter-area mode. But also here we can conclude that the impact of the parameters of the voltage controller on the inter-area oscillations is small.

Figure 4.5 shows the right eigenvectors of generator speed deviations together with that of the wind farm reactive power deviation. It is noticed that, the WF reactive power deviation eigenvector leads the receiving end generators speed deviations by around 130 degrees. The lead angle is increased slightly when the gain is increased. It is also noted that the WF voltage controller does not participate in the inter-area mode.

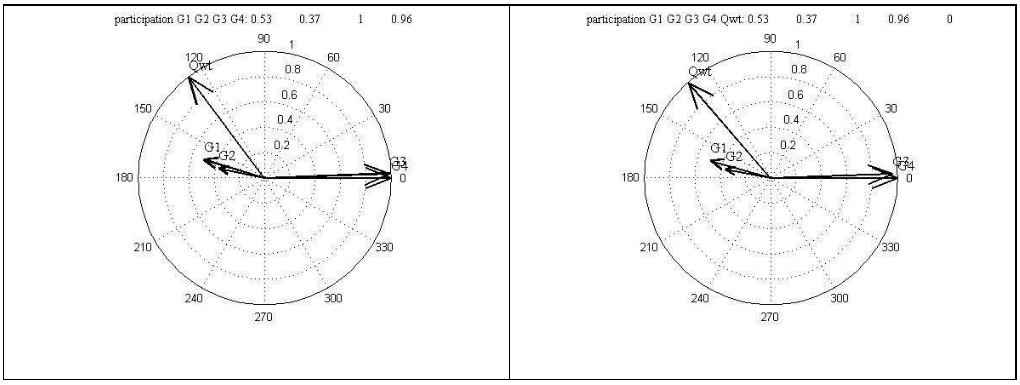


Figure 4.5 Normalized right eigenvectors of generators rotor speed deviations (mode shapes) together with WF reactive power power deviations corresponding to the inter-area mode. Corresponding participation factors are also printed. Parameter combination 4 (left) and 15 (right).

WF @BUS 08 (on the tie line):

The damping of the inter-area mode is calculated for few different WF voltage controller combinations. The results are shown in Table 4.5.

Table 4.5: Damping of the inter-area mode for few selected voltage controller parameter combinations

| Voltage controller parameter combination | Damping of the inter-area mode |
|---|---|
| ***No WF*** | *6.8%* |
| **1.** | 7.8% |
| **2.** | 8.1% |
| **3.** | 8.7% |
| **4.** | 4.9% |
| **7.** | 4.3% |
| **10.** | 4.6% |
| **12.** | 4.4% |
| **15.** | 4.9% |

We will again consider parameter combination 4 and 15. At these parameter combinations, the wind farm voltage controller's forced vibration response- from a disturbing voltage to the wind farm reactive power- has a phase angle of around 170 degrees while the gain varies. And the effect of the increasing gain at 0.35 Hz on the damping of the inter-area mode is not so noticeable.

Contrary to the earlier two locations, we observe a large impact of the voltage-control parameters on the damping. For parameter combinations 1, 2 and 3 the damping is increased; for combinations 4, 7, 10, 12 and 15 the damping is reduced.

Figure 4.6 shows the right eigenvectors of generator speed deviations together with the wind farm reactive power deviation for parameter combination of 4 and 15. It is noticed that the WF reactive power deviation eigenvector is located in between the sending and receiving end generators speed eigenvectors. WF reactive power deviation eigenvector lags the sending end generators speed eigenvectors by more than 90 degrees and leads that of receiving end generators by less than 90 degrees. The lag/lead angle is around 15 degrees. It is interesting to note that the WF voltage controller has slight participation in the inter-area mode when it is located on a tie line.

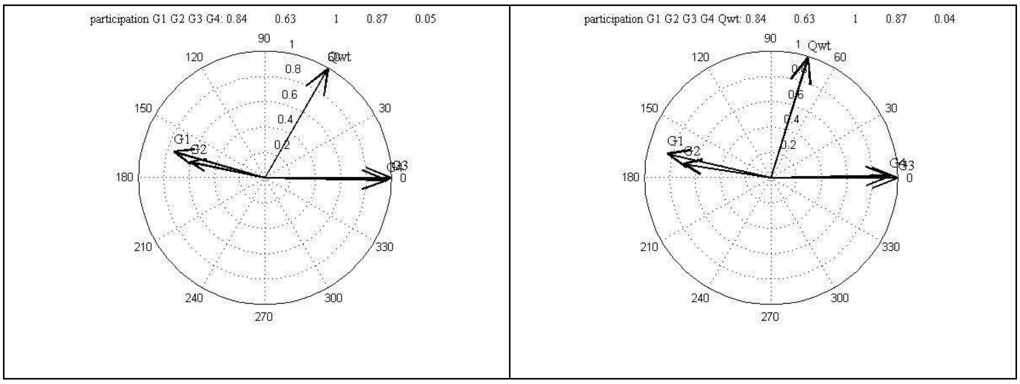


Figure 4.6 Normalized right eigenvectors of generators rotor speed deviations (mode shapes) together with WF reactive power deviations corresponding to the inter-area mode. Corresponding participation factors are also printed. Parameter combination 4 (left) and 15 (right).

We will also consider another parameter combination (combination 1). At this parameter combination, the wind farm voltage controller's forced vibration response- from a disturbing voltage to the wind farm reactive power- has a phase angle of around 185 degrees while the gain is minimum. And the effect of the decreasing gain and increasing phase angle on the damping of the inter-area mode is quite fascinating. The damping of the inter-area mode has increased from the base case value when a wind farm is connected. However, the parameter combination will produce an inferior transient performance in terms of voltage recovery after network faults.

Figure 4.7 shows the right eigenvectors of generator speed deviations together with that of the wind farm reactive power deviation. It is noticed that the WF reactive power deviation eigenvector lags the sending end generators speed eigenvectors by less than 90 degrees but leads the receiving end generators speed eigenvectors by more than 90 degrees. The lead lag angle is around 10-15 degrees in this case. Comparing this eigenvectors with that of Figure 4.6 shows that when the WF reactive power deviation eigenvector lags the speed eigenvectors of the sending end generators, it increases the damping of the inter-area oscillation when the WF is located on the tie line.

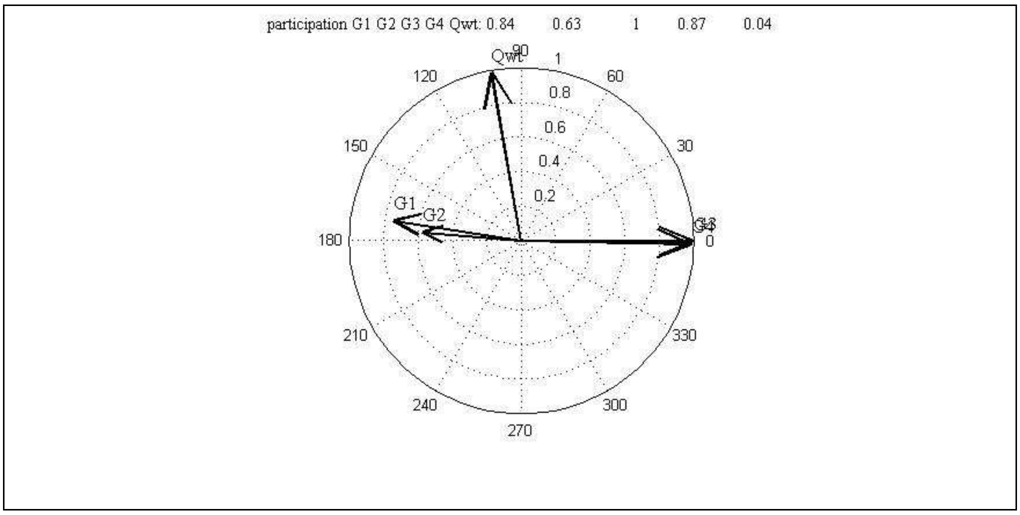


Figure 4.7 Normalized right eigenvectors of generators rotor speed deviations (mode shapes) together with WF reactive power power deviations corresponding to the inter-area mode. Corresponding participation factors are also printed. Parameter combination 1.

The studied parameter combinations considered above result in different time response characteristics of the controller. However, in FI there is a requirement that the WFs voltage controller response should have a rise time of 1 sec. It is noticed that the GE default values do not result in a 1s rise time in the study system considered. To be able to achieve a 1 sec rise time, the following parameters have been varied within the manufacturer specified range: Kpv, Kiv, KQi. The above mentioned calculations are repeated using these new sets of controller values that give 1s rise time. The results are shown in Table 4.6.

Table 4.6: Frequency and damping constant of inter-area oscillation (modified voltage controller values to achieve a 1s rise time requirement)

| Single WF location | Load characteristics | |
|---|---|---|
| | Constant current (f, ζ) | Constant power (f, ζ) |
| *No WF* | *0.37 Hz, 6.8%* | *0.35 Hz, 2.3%* |
| @BUS 5 *sending end* | 0.38 Hz, 7.0% | 0.35 Hz, 2.6% |
| @BUS 6 –‘’- | 0.38 Hz, 6.8% | 0.36 Hz, 2.1% |
| @BUS 7 –‘’- | 0.39 Hz, 6.4% | 0.36 Hz, 1.9% |
| @BUS 8 ***middle of tie*** | 0.41 Hz, 5.4% | 0.40 Hz, 0.9% |
| @BUS 9 *receiving end* | 0.37 Hz, 6.5% | 0.37 Hz, 2.0% |
| @BUS 10 –‘’- | 0.38 Hz, 6.2% | 0.35 Hz, 2.2% |
| @BUS 11 –‘’- | 0.38 Hz, 6.8% | 0.34 Hz, 2.5% |

As can be seen from the table, the studied WF located in the sending end of the system may tend to improve the damping of the 0.35 Hz inter-area mode. However, the studied WF located in the receiving end of the system may tend to reduce the damping of the 0.35 Hz inter-area mode. However, it is to be noted that the positive or the negative impact on the damping is rather small. But the studied WF in the middle of the tie-line may significantly reduce the damping of the 0.35 Hz inter-area mode.

This table confirms the earlier conclusions that the impact is small for locations close to the generators, but big for locations near the tie-line.

## 4.4 Full active power production from the wind farm

In this section, we will consider full power production from the WF. In the first test, we will accommodate the incoming wind power by reducing the production from conventional generators located in the same area. In this way the tie line flow will be kept unchanged. We have considered two locations, bus 6 sending end and bus 10 receiving end. The GE specified default values of the voltage controller are used. The results are shown in Table 4.7.

Table 4.7: Frequency and damping constant of inter-area oscillation (generation reduced from WF area)

| Single WF location | Full wind generation | *No production from WF* |
|---|---|---|
| | (f, ζ) | (f, ζ) |
| *No installed WF* | *(0.37 Hz, 6.8%)* | |
| @BUS 6 *sending end* | 0.39 Hz, 7.5% | *0.38 Hz, 7.1%* |
| @BUS 10 *receiving end* | 0.38 Hz, 6.2% | *0.37 Hz, 5.7%* |

At the sending end, the presence of WF has increased the damping of the inter-area oscillations compared to the ‘no production’ scenario. The improvement is two folds- one from positive contribution from the voltage controller and another one is from the displaced generation from the conventional generators due to the wind power.

In the receiving side, the presence of WF has increased the damping of the inter-area oscillations compared to the ‘no production’ scenario. However, this contribution is due to the displaced generation from the conventional generators thanks to the wind power.

In the second test, we will accommodate the incoming wind power by taking a generator out from the same area and adjusting the load of the system so that the tie line flow remains the same. We have considered two locations, bus 5 sending end and bus 11 receiving end. The results are shown in Table 4.8.

Table 4.8: Frequency and damping constant of inter-area oscillation (generator taken out of service from WF area)

| Single WF location | Full wind generation | *No production from WF* |
|---|---|---|
| | (f, ζ) | (f, ζ) |
| *No installed WF* | *(0.37 Hz, 6.8%)* | |
| @BUS 5 *sending end* | 0.46 Hz, 5.4% | *0.38 Hz, 7.1%* |
| @BUS 11 *receiving end* | 0.48 Hz, 10% | *0.38 Hz, 6.7%* |

It is noticed that when the incoming wind power is accommodated at the sending end by taking out a conventional generator, the damping of the inter-area mode is reduced compared to the 'no production' scenario. The frequency of the inter-area mode is also increase. However, when the wind power is accommodated at the receiving end by taking out a conventional generator, the damping of the inter-area mode is increased compared to the 'no production' scenario.

## 4.5 Summary

For inter-area oscillations around 0.36 Hz, the following observations are made based on the calculations performed in the IEEE two-area model:

- The impact of wind farms connected close to the sending or receiving end is small; where it has been ensured in the study that the power transfer through the tie line is the same for the cases with and without wind farms.
- A wind farm connected close to the tie line, reduces the damping and therewith results in a higher level of inter-area oscillations. Also here the power transfer was kept the same for the cases with and without wind farms.
- The parameters of the wind-farm controllers have only small influence on the damping for locations near the sending and near the receiving end. For a location close to the tie line, the damping is reduced by the presence of the wind farm.
- When the power transfer is not kept constant, adding wind farms on the sending end will increase the power transfer through the tie line. This reduces the damping. In the same way, adding wind farms on the receiving end reduces the power transfer and increases the damping. This is most likely due to the change in transfer, not due to the wind-farm controllers.
- An important conclusion from the study in this simple model is that the impact is strongly location dependent. The same wind farm, with the same controller shows a slight improvement at one location, but a huge deterioration at another location. This makes that it may be difficult to set general requirements on wind-farm controllers without a study considering the whole Nordic grid.

# 5 Inter-area oscillations in the Nordic grid as affected by planned wind farms

## 5.1 Description of the systems studied

### 5.1.1 Original Nordic-32 system

The description of the original Nordic-32 test system can be found in [8]. A diagram of the system is shown in Figure 5.1.

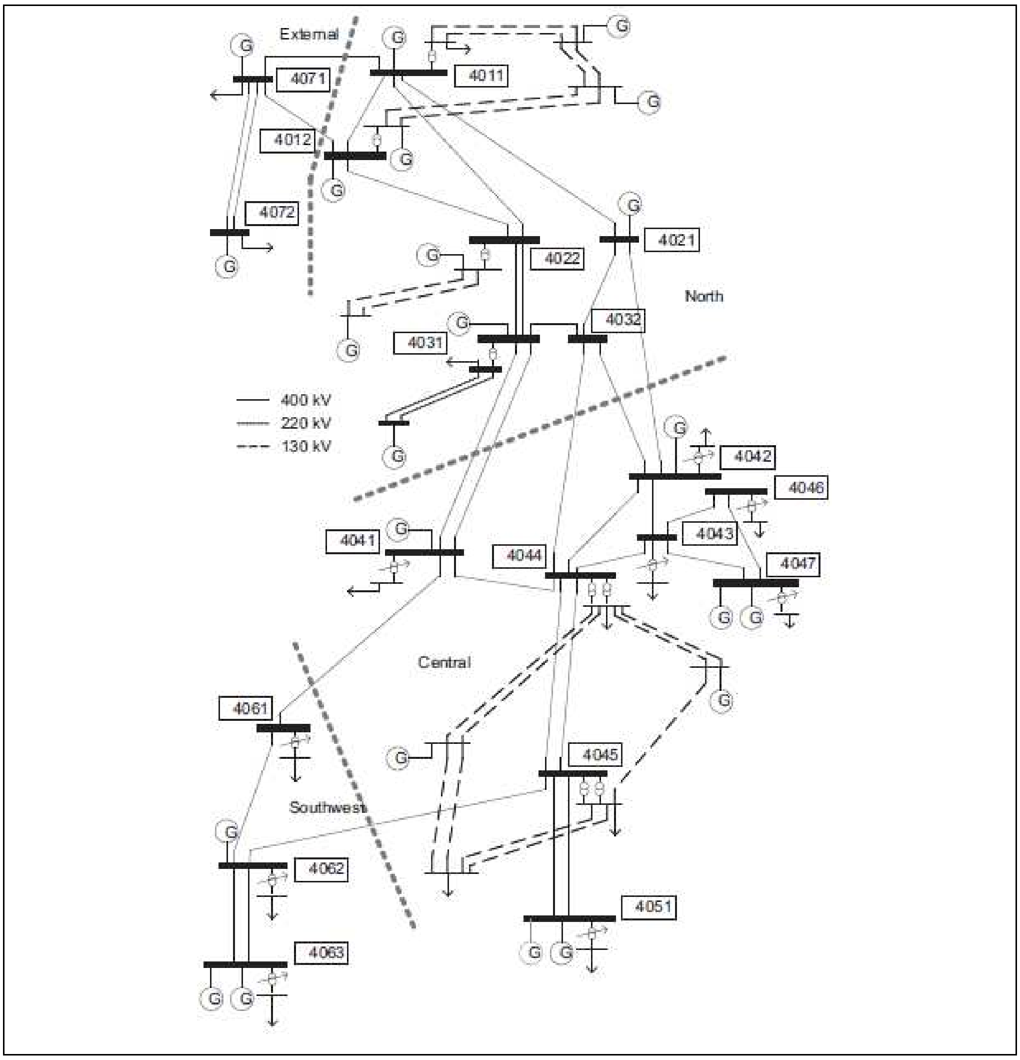


Figure 5.1 Original Nordic-32 model.

The eigenvalues of the system is calculated using PSSE LSYSAN, and is shown in Figure 5.2. The system exhibits 17 low damped oscillation modes (damping less than 15%) within the frequency range 0.6 to 1.6 Hz.

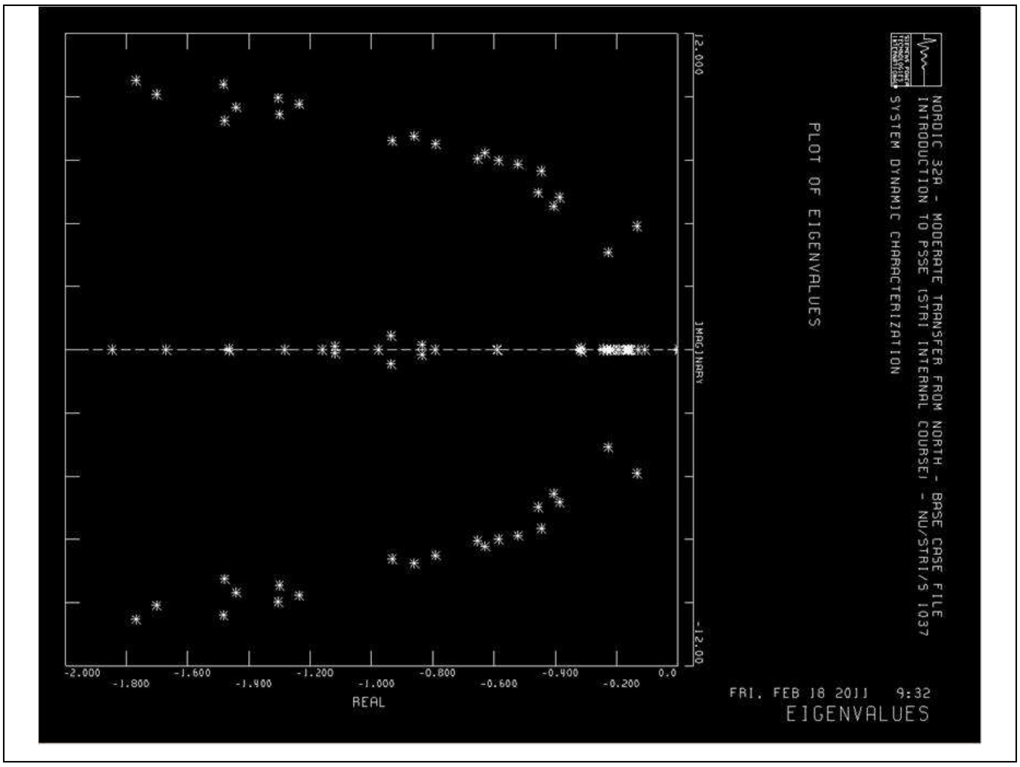


Figure 5.2 Eigenvalues of the original Nordic-32 system

The mode shapes of the rotor speed deviations of few generators in south of SE and FI corresponding to the 0.6 Hz are shown in Figure 5.3. This represents a mode where generators in FI oscillate against that of south SE. However, in reality such mode has a frequency of 0.35 Hz. So the test system cannot be directly used to assess the impact of WF voltage controllers on the damping of the inter-area mode. The original Nordic-32 system represents the Swedish part of the grid quite well but does not include the Norwegian and Finnish part of the system in detail. So, modifying the Nordic-32 system with these missing parts was necessary.

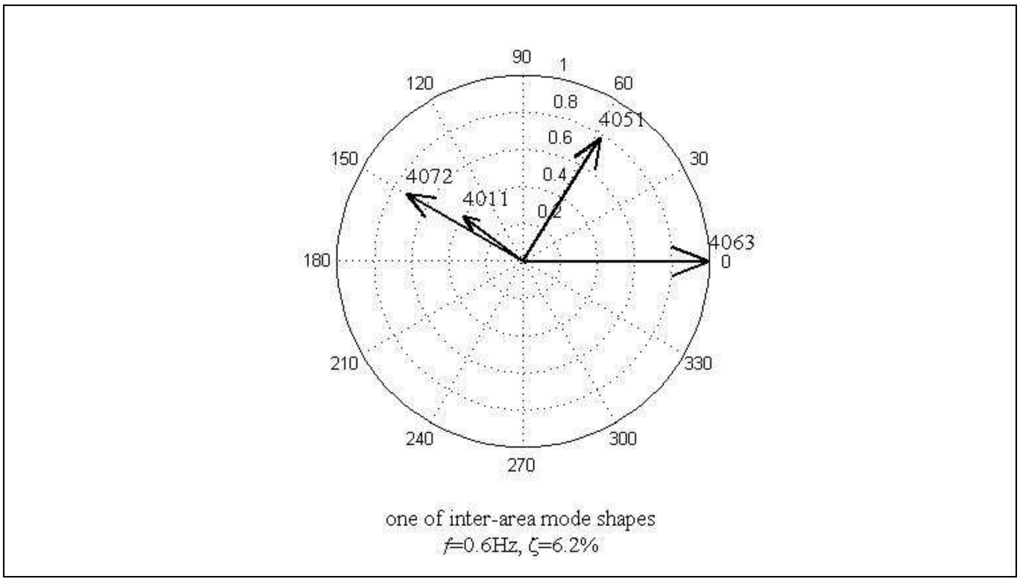


Figure 5.3 0.6Hz mode shapes.

### 5.1.2 Modified Nordic-32 grid

A simplified version of the interconnected Nordic system was obtained from Professor Kjetil Uhlen from Sintef/NTNU through private communication. The model has a relatively detailed representation of the Norwegian part of the interconnected system. A schematic diagram of the system is shown in Figure 5.4.

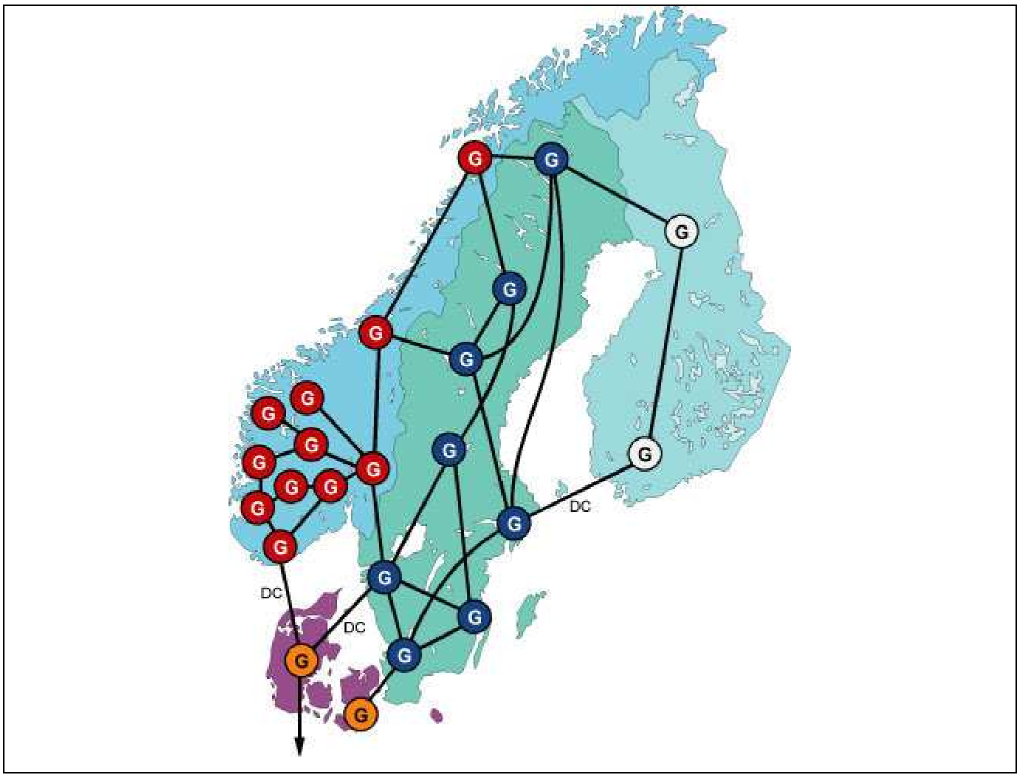


Figure 5.4 A diagram of a simplified Nordic system (source: Sintef).

The Norwegian part of the grid has been added to the original Nordic-32 system with proper scaling to include the Norwegian part. The Finnish part of the network has been augmented with 6 generators with help from Fingrid. A PSSE SLD diagram of the resulting augmented grid is shown in Figure 5.5.

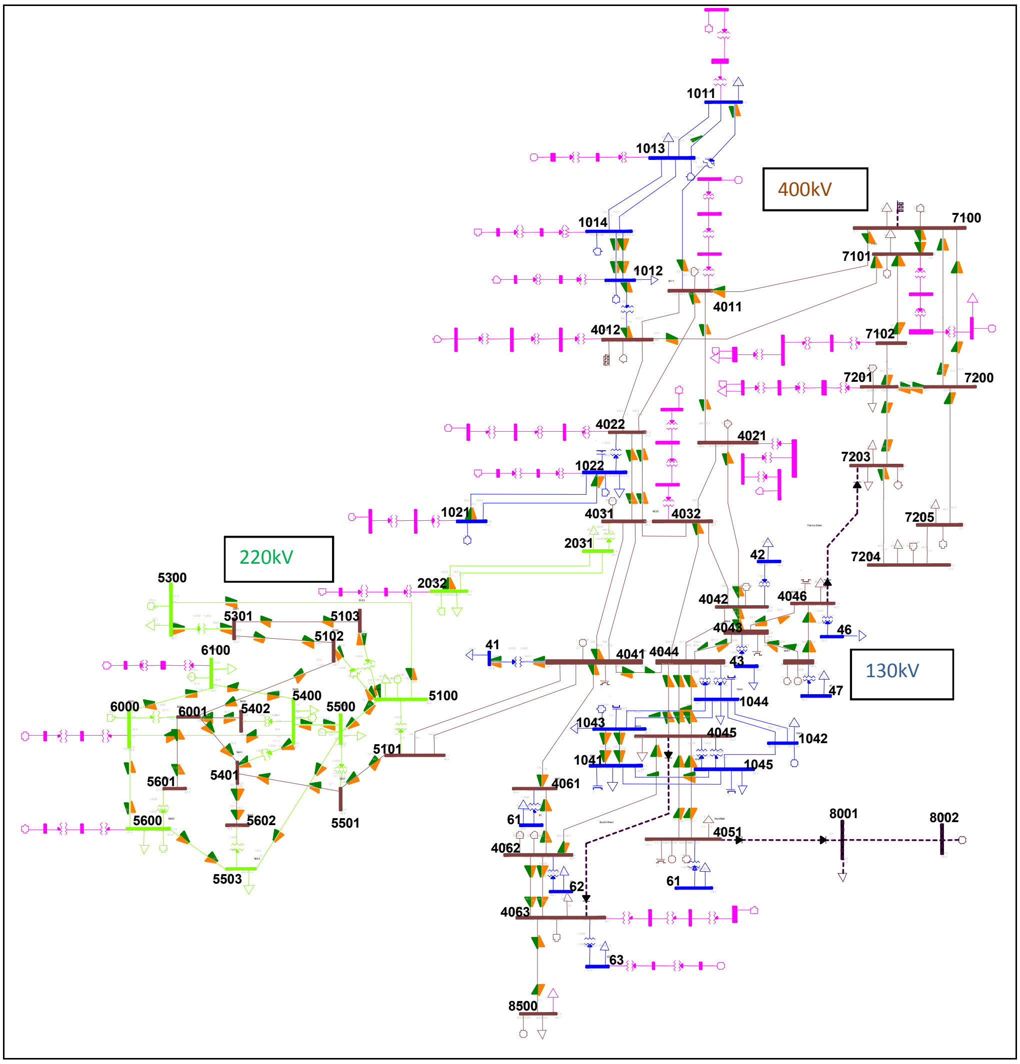


Figure 5.5 Modified Nordic-32 grid including the augmented Norwegian and Finnish part.

The calculated eigenvalues of the modified Nordic-32 grid are shown in Figure 5.6.

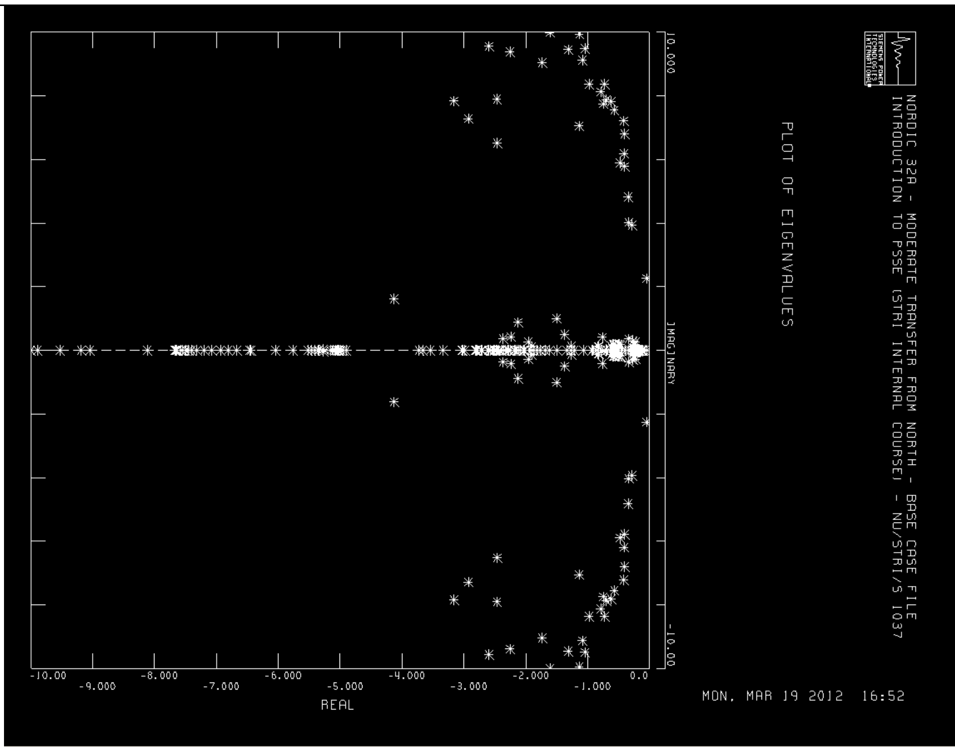


Figure 5.6 Eigenvalues of the modified Nordic-32 grid.

From the calculated eigenvalues, a pair of low damped complex eigenvalue is identified at frequency 0.35 Hz. Further eigenvector analysis of the mode reveals that at this frequency generators in south of FI oscillates against that of south of NO and SE. The calculated mode shapes is shown in Figure 5.7. The modified system now exhibits an inter-area mode that represents the actual mode observed in the Nordic grid. The modified model can now be used to assess the impact of planned WFs integration on the damping of the 0.35 Hz inter-area mode. In our base case network model of the modified system, export from FI to SE is negligible.

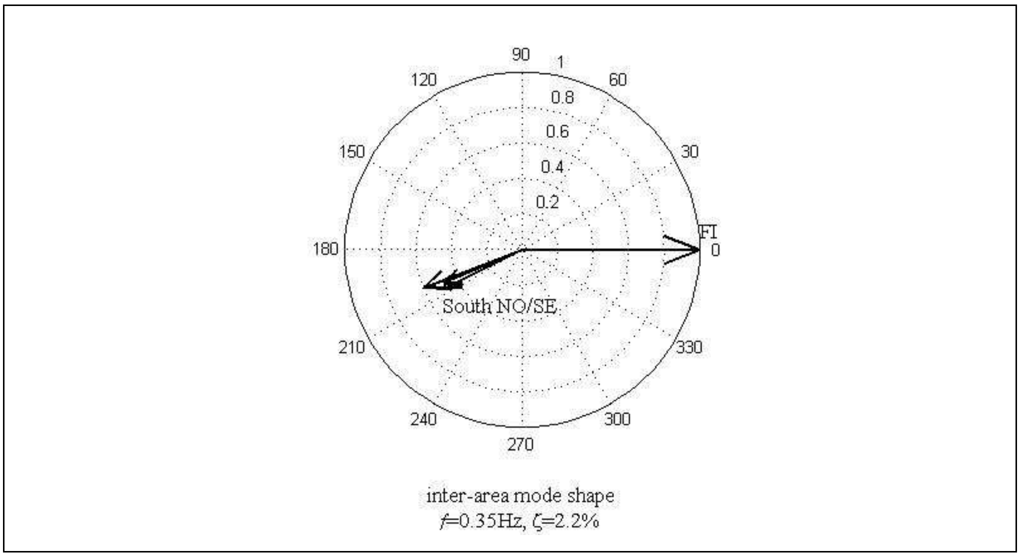


Figure 5.7 0.35Hz mode shapes.

From the participation factors, we found that generators in south FI are the highest participants in this mode. So any change in the Finnish part of the network has the potential to affect this mode.

It is to be noted that, the power flows from the northern part to the southern part of the system. So the generators in FI are at the sending end of the system and the generators in south SE and NO are at the receiving end.

### 5.1.3 Location of planned wind farms

The locations of planned WFs in the Nordic grid are shown in Figure 5.8. The Swedish and Norwegian scenarios are based on a EU2020 scenario [10]. The Finnish scenario is received from Fingrid. The locations of the WFs are based on the discussions with the project reference group members. Total WFs in NO is 2500 MW, in SE is 6000 MW and in FI is 3000 MW. It is to be noted that the modified system is a one third scaled down version of the original system. So the 500 MW WF is a 160 MW WF in our test system.

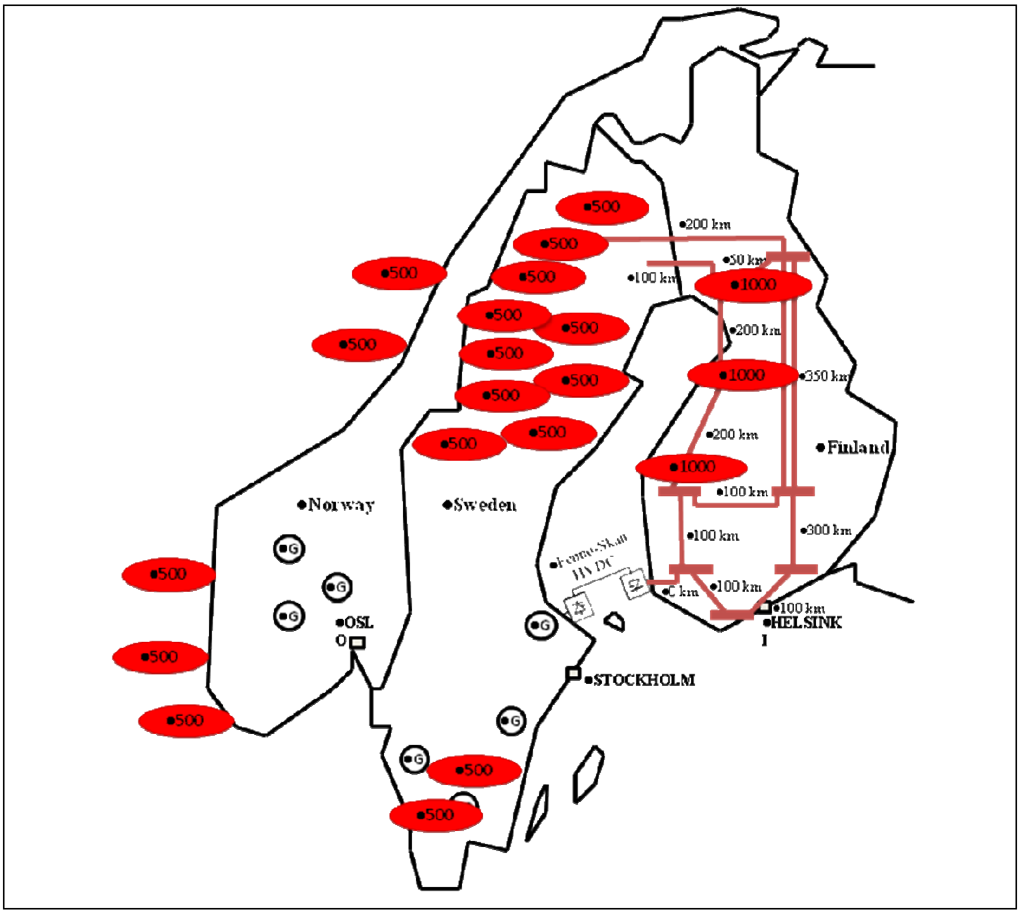


Figure 5.8 Location of planned WFs.

## 5.2 Study approach

As has been mentioned earlier, generators in FI have highest participations in the 0.35 Hz mode, so any change in the Finnish part of the network has the potential to affect this mode. It is suspected that the planned WFs in FI may affect the mode. For this region, the WFs in FI are treated separately to identify how the planned WFs in FI will influence the 0.35 Hz mode. To do so, we have again adopted the ‘no production’ scenario where WFs are connected to the grid without injecting any active power into the grid. In this way we will be able to assess the impact of the WF voltage controller on the 0.35Hz mode. Later a full production scenario will be considered. The wind power will be fully exported to SE using the existing tie lines between FI and north of SE.

Later all planned WFs in NO, SE and FI will be included. Two different cases will be analyzed. However, we will NOT include a ‘no production’ scenario for the case with WFs in the three countries.

## 5.3 Wind farms in Finland only

### 5.3.1 System description

In the base case modified Nordic-32 system, we have added three WFs each with 165 MVA rated capacity (in reality each WF is 500MW). Both the GE default values of the voltage controller and other values of the controller are used in the studies.

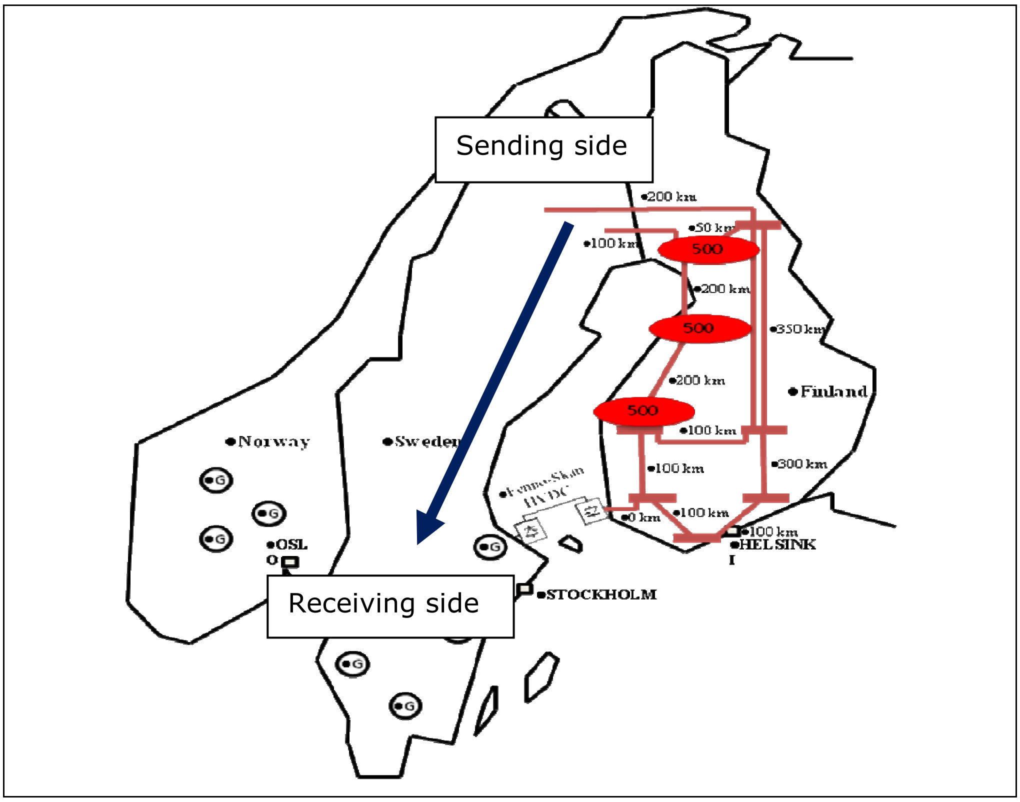


Figure 5.9 Planned WFs in FI

### 5.3.2 Analysis

The results from the eigenvalue analysis are shown in Table 5.1. In this calculation the default values of the voltage controller are used. It is found that the action of WF voltage controllers in FI will increase the damping of the inter-area mode. The improvement in damping is around 1.5% compared to the base case scenario with no WFs. The result agrees with our previous generic conclusion made on Chapter 4 that WFs voltage controllers located at the sending end away from load centres will increase the damping of the 0.35 Hz inter-area mode.

Table 5.1: Frequency and damping constant of inter-area oscillation (default values of the controller)

| | Frequency and damping of inter-area mode |
|---|---|
| Base case | 0.35 Hz, 2.2% |
| WF in FI only (zero prod.) | 0.36 Hz, 3.7% |
| WF in FI only (full prod. 450MW export to SE) | 0.35 Hz, -0.5% |
| WF in FI only (full prod. 450MW export to SE) – *WF as negative constant load* | 0.34 Hz, -3.7% |

In the full production case, the 450 MW wind power, which is exported to SE, will make the oscillation mode unstable. A contingency will make the scenario even worse. So the export to SE from FI needs to be kept lower than 400MW considering a tie line trip contingency.

The corresponding mode shapes are shown in Figure 5.10. Only some of the generators in FI, SE and NO are shown. As can be seen from the figure, the WF reactive power deviation eigenvector lags the speed eigenvectors of the sending end generators (generators in south of FI) which also agrees with our generic conclusions made in Chapter 4.

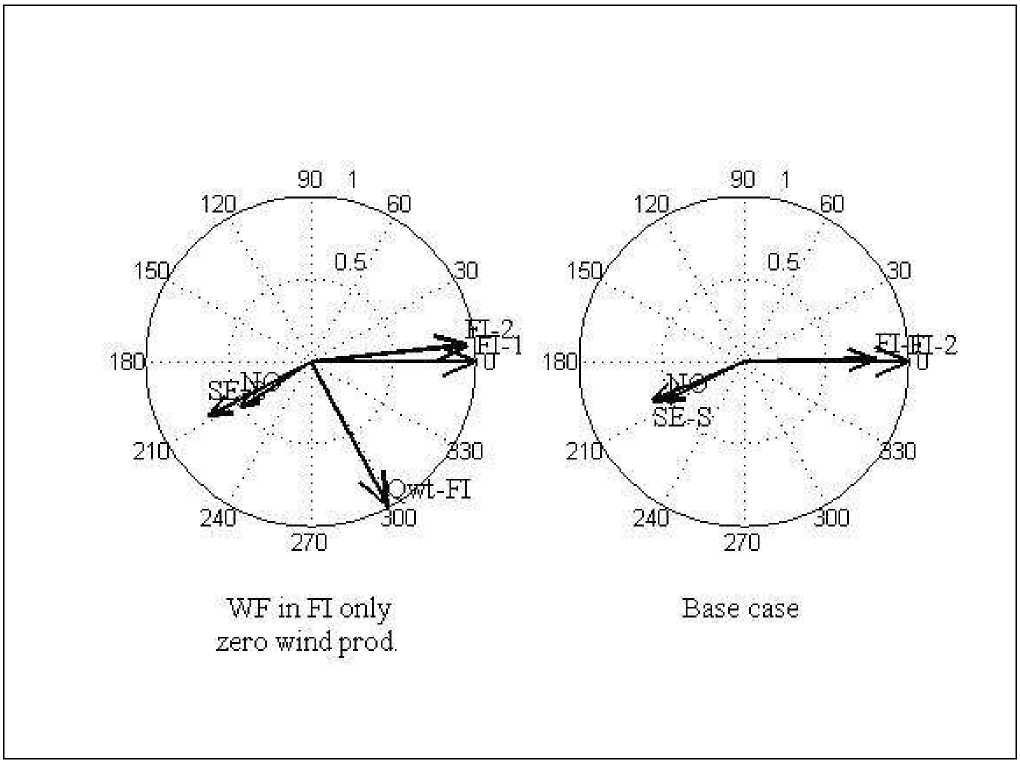


Figure 5.10 0.35 Hz mode shapes. Together with the WF reactive power deviations.

However, as has been mentioned earlier, in FI there is a requirement that the WFs voltage controller response should have a rise time of 1s. It is noticed that the GE default values do not result in a 1s rise time. To be able to achieve a 1s rise time, the following parameters have been varied within the manufacturer specified range: Kpv, Kiv, KQi. The above mentioned calculations are repeated using these new sets of controller values that give 1 sec rise time. The results are shown in Table 5.2.

Table 5.2: Frequency and damping constant of inter-area oscillation (updated values of the WF voltage controller to achieve 1 sec rise time)

| | Frequency and damping of inter-area mode |
|---|---|
| Base case | 0.35Hz, 2.2% |
| WF in FI only (zero prod.) | 0.36Hz, 3.5% |
| WF in FI only (full prod. 450MW export to SE) | 0.35Hz, -0.8% |
| WF in FI only (full prod. 450MW export to SE) – *WF as negative constant load* | 0.34Hz, -3.7% |

As can be seen from the table, the studied WF voltage controller tuned to achieve a 1s rise time may have a positive impact on the damping of the 0.35 Hz inter-area mode. The result agrees with our previous generic conclusion made in Chapter 4 that the studied WFs voltage controllers located at the sending end away from load centres will increase the damping of the 0.35 Hz inter-area mode.

The differences between Table 5.2 and Table 5.1 are small; the earlier conclusions are therefore still valid.

### 5.3.3 Comments

The sole impact of the planned WF voltage controllers in FI, as has been considered in the study, on the 0.35 Hz mode may in general be positive. However, when the production from WFs is maximum and it is exported to SE increasing the tie line flow, the mode becomes negatively damped. It is found that when 450 MW is exported from FI to SE, the damping becomes negative. The negative damping of the 0.35 Hz mode due to the planned WFs as has been considered in the study cannot be directly attributed to the WF voltage controllers, instead it a ramification of the changed power flow (increased tie line flow) caused by the introduction of a new production unit.

## 5.4 Inclusion of all planned wind farms

### 5.4.1 System description

In this set of tests all planned WFs will be included. In a previous figure, Figure 5.8, the locations of all planned WFs are shown. The default values of WF voltage controller will be used. Another set of controller values that will results in a 1sec rise time will also be used in the calculations.

### 5.4.2 Study approach

In this set of studies, we will not include a 'zero production' scenario from WFs. Two separate cases will be considered. Full production from WFs will be considered. Power balance will be made by reducing generation from existing flexible generators, by taking few generators out of service, by considering normal load growth, and by increasing power transfer to neighbouring countries.

### 5.4.3 Case-1

In case-1 the export to SE from FI is almost 280 MW and export from NO to SE is 130 MW. In this case hydro production in North of FI and SE is low while nuclear and wind power production is high. Power export to neighbouring countries is high.

From the eigenvalue calculation, we found that the inter-area mode of interest has 3.5% damping and the frequency is 0.37 Hz, when the default voltage controller values are considered. The corresponding mode shapes are shown in Figure 5.11. In the mode shape diagram, WF reactive power deviations eigenvectors are also shown. It is found that, the reactive power deviation of WFs located in FI and north of SE lags the speed eigenvectors of generators in FI. However, the reactive power deviation of WFs located in NO leads the speed eigenvectors of generators in south NO.

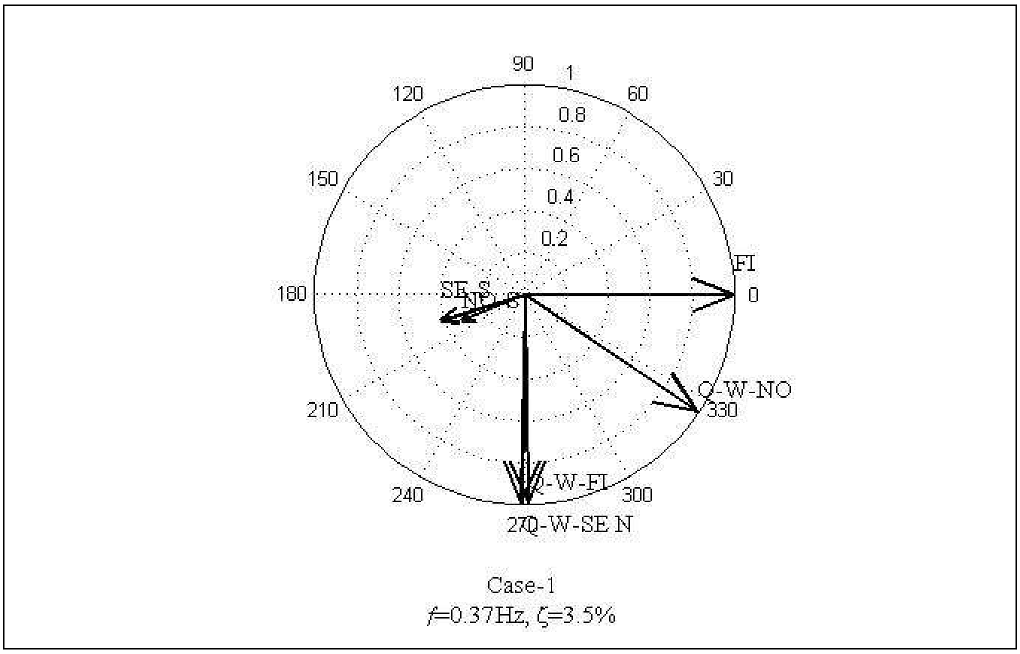


Figure 5.11 0.37 Hz mode shapes

When modified values of the voltage controller are used that result in a 1s rise time, the frequency and damping of the inter-area mode becomes 0.38 Hz and 4.6% respectively. The WF voltage controller parameters tuned to achieve a 1s response time may result in a better damping of the 0.35 Hz mode compared to the GE default values.

### 5.4.4 Case-2

In case-2 the export to SE from FI is almost 300 MW and export from NO to SE is 230 MW. In this case hydro production in North of FI and SE is moderate while nuclear and wind power production is high. Power export to neighbouring countries is high.

From the eigenvalue calculation, we found that the inter-area mode of interest has 6.8% damping and the frequency is 0.39 Hz, when the default voltage controller values are considered. The corresponding mode shapes are shown in Figure 5.12. In the mode shape diagram, WF reactive power deviations eigenvectors are also shown. It is found that, the reactive power deviation of WFs located in FI and north of SE lags the speed eigenvectors of generators in FI. However, the reactive power deviation of WFs located in NO leads the speed eigenvectors of generators in south NO.

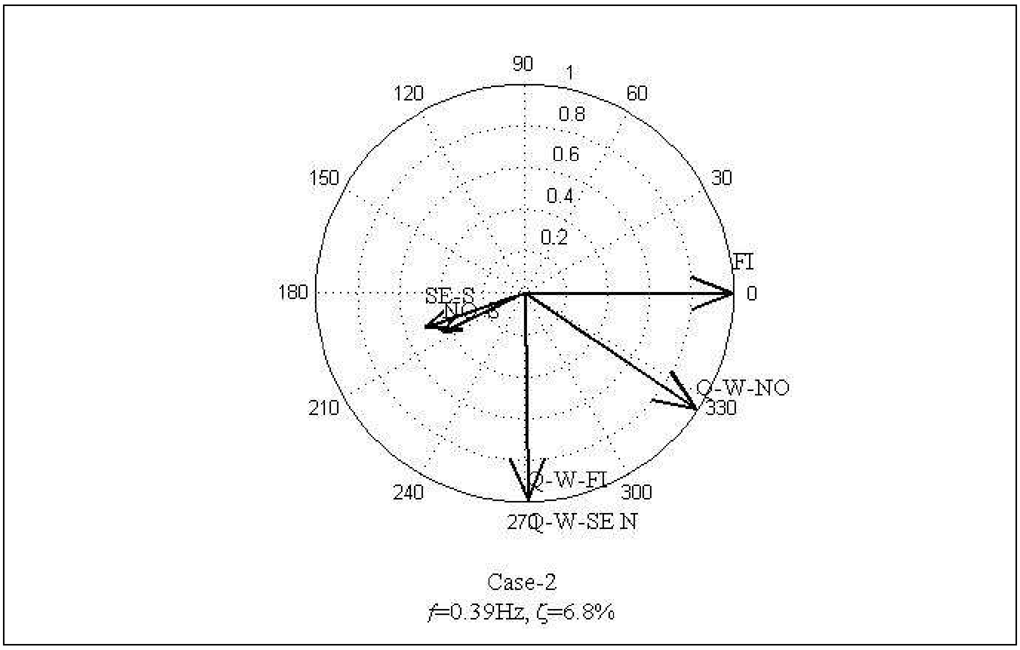


Figure 5.12 0.39 Hz mode shape.

When modified values of the voltage controller are used that result in a 1 sec rise time, the frequency and damping of the inter-area mode becomes 0.39 Hz and 6.3% respectively. The WF voltage controller parameters tuned to achieve a 1 sec response time may result in a slightly less damping of the 0.35 Hz mode compared to the GE default value.

### 5.4.5 Discussion

When all the planned WFs are included as has been considered in the work, it is found that the damping may improve compared to the studied base case. Again, the improvement of the damping may be due to the changed system load flow conditions.

# 6 Conclusions and future research

## 6.1 Conclusion

### 6.1.1 Disturbance rejection capability of the WF voltage controller

The disturbance rejection capability of the studied WF voltage controller is analyzed. From the studied case considered, it is found that a 0.1 Hz change in frequency (phase angle remains close to 180 degrees) is quite effectively rejected by the controller. The particular WF voltage controller exhibits a high gain at 0.35 Hz. The gain and phase characteristics of the voltage disturbance rejection capability of the voltage controller at 0.35 Hz can be adjusted by varying different voltage controller parameters which will also affect the rise time of the voltage controller.

### 6.1.2 Study on an IEEE two-area system

The impact of wind farms connected close to the sending or receiving end is small; where it has been ensured in the study that the power transfer through the tie line is the same for the cases with and without wind farms.

A wind farm connected close to the tie line reduces the damping and therewith results in a higher level of inter-area oscillations. Also here the power transfer was kept the same for the cases with and without wind farms.

The parameters of the wind-farm controllers have only small influence on the damping for locations near the sending and near the receiving end. For a location close to the tie line, the damping is reduced by the presence of the wind farm.

When the power transfer is not kept constant, adding wind farms on the sending end will increase the power transfer through the tie line. This reduces the damping. In the same way, adding wind farms on the receiving end reduces the power transfer and increases the damping. This is most likely due to the change in transfer, not due to the wind-farm controllers.

An important conclusion from the study in this simple model is that the impact is strongly location dependent. The same wind farm with the same controller shows a slight improvement at one location, but a huge deterioration at another location. This makes that it may be difficult to set general requirements on wind-farm controllers without a study considering the whole Nordic grid.

### 6.1.3 Study on the modified Nordic-32 system – WFs in FI only

From the limited studied case considered, it is found that the sole impact of the planned WFs' voltage controllers in FI, on the 0.35 Hz mode is in general positive. This conclusion is drawn based on studies that consider GE specified values of the voltage controller, as well as, other combinations of the GE WF voltage controller parameters resulting in a 1 sec rise time. However, it is found that when the production from WFs is maximum and it is exported to Sweden (SE) increasing the tie line flow, the mode becomes negatively damped. The negative damping of the 0.35 Hz mode due to the planned WFs cannot be directly attributed to the WF voltage controllers, instead it could be a ramification of the changed system power flow (increased tie line flow) caused by the introduction of a new production unit.

### 6.1.4 Study on the modified Nordic-32 system – WFs in NO, FI, SE

Based on the limited studies, it is found that when all the planned WFs are included, the damping of the inter-area mode is improved compared to the case where no wind power was considered. Again, the improvement of the damping could be due to the changed system load flow and generation dispatch conditions considered. Other operational states of the system may indicate a different result.

Accordingly, the presence of wind farms in Finland results in an increased damping both for local consumption and for export of the produced power to Sweden through the north. Changing the settings of the controller from the GE default values to values that comply with the 1-second rise-time requirement has only minor impact on the results. The general conclusions remain valid. Considering wind power throughout Sweden, Norway and Finland has only minor impact on the inter-area oscillations for the cases studied.

## 6.2 Future research

The following topics are proposed for future research:

1. The impact of different WF controllers on the secure transfer capacity, e.g. between Sweden and Finland, when inter-area oscillations are the limiting factor. The IEEE model showed a reduced damping for some locations. This was not observed for the Nordic-32 model. The results from the IEEE model should be analysed in more depth to find out if there are such advantageous locations in the Nordic grid as well.
2. Can the disturbance-rejection capability of a wind-farm controller (as studied in Chapter 3) be used to predict if the controller will improve or deteriorate the inter-area oscillations? Such a study should include the relation between the disturbance-rejection capability (or the transfer function at the inter-area oscillation frequency) and the reduction or increase of the damping. A logical next step would be to develop relations between change in damping and change in secure transfer capacity.

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