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A NOVEL APPROACH FOR GRID INTERACTION EFFECTS WITH WIND TURBINE INVERTER ROBUST LOOP-SHAPING CONTROL

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Abstract—This paper presents a digital H∞ controller based grid connected WECS. The mechanical dynamics are controlled by PI based pitch angle control system while generator-side converter and grid-side inverter are regulated via the digital H∞ controller. The proposed method is compared with the conventional PI controller method and the fuzzy controller method. An H∞ robust control of wind turbine (WT) inverters employing an inductor-capacitor-inductor (LCL) filter is proposed in this project. The controller dynamics are designed for selective harmonic filtering in an offshore transmission network subject to parameter perturbations. Parameter uncertainty in the network originates from the grid and the number of WTs connected. Power converter-based turbines inject harmonic currents, which are attenuated by passive filters. A robust high-order active filter controller is proposed to complement the passive filtering. The H∞ design of the control loop enables desired tracking with integral effect while bounding the induced change. The design was tested in an aggregated model of the London Array offshore wind power plant and compared with traditional Proportional- Integral (PI) controller designs. Robust stability and performance and a reduction of control effort by 25% are obtained over the full envelope of operation.

KEY INDEX: Wind Turbine (WT) Inverters, Proportional- Integral (PI) Controller.

I. INTRODUCTION

However, the recognition that their aggregated behavior may have an impact on the bulk power system is paving the path for new transmission-type regulations. As the installed power of DGs grows, grid codes are being modified to consider provision of ancillary services such as: controlled active power output, steady-state voltage regulation, and fault ride-through (FRT) capabilities [3]. The latter may require DGs not only to remain connected in the event of a fault, but also to support the grid through the injection of reactive power. In the German MV grid code introduced in 2008 [4], this requirement is already included under the rubric of “dynamic grid support.” Photovoltaic (PV) power generation represents a key technology for realizing the DG concept. As the cost of PV panel production continues to decrease, it is expected that solar power generation will be competitive with other forms of renewable energy, and hence massively deployed [5]. PV systems are connected to the ac grid via a power electronic interface. This interface may include a boost dc/dc converter, and an inverter.The two-level voltage-source inverter (VSI) is widely adopted as the configuration of choice by most major PV system manufacturers [6], [7]. When the boost converter is eliminated by connecting an appropriate number of PV panels in series, the resulting architecture is referred to as single-stage topology. This architecture is more efficient and economical than its two-stage counterpart under homogeneous irradiance conditions [8], [9], and is the subject of this paper. this paper proposes a novel FRT control scheme for PV inverters able to perform “dynamic grid support” through the injection of reactive power under unbalanced grid faults. The control scheme enables adjustable power quality as a tradeoff between power ripple and current harmonics, and therefore can be adapted to comply with different operational standards. The inverter is operated under current control mode, and the controller is implemented in the α–β stationary frame based on the SVFT concept. No rotational transformation is required, and zero steady-state error is ensured for the positive sequence harmonic components selected to be controlled.

II. DC- AC CONVERTER (INVERTER):

An inverter is an electrical device that converts direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.Solid-state inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utility high-voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels or batteries.There are two main types of inverter. The output of a modified sine wave inverter is similar to a square wave output except that the output goes to zero volts for a time before switching positive or negative. It is simple and low cost (~$0.10USD/Watt) and is compatible with most electronic devices, except for sensitive or specialized equipment, for example certain laser printers. A pure sine wave inverter produces a nearly perfect sine wave output (<3% total harmonic distortion) that is essentially the same as utility-supplied grid power. Thus it is compatible with all AC electronic devices. This is the type used in grid-tie inverters. Its design is more complex, and costs 5 or 10 times more per unit power (~$0.50 to $1.00USD/Watt).[1] The electrical inverter is a high-power electronic oscillator. It is so named because early mechanical AC to DC converters was made to work in reverse, and thus was "inverted", to convert DC to AC. The inverter performs the opposite function of a rectifier.

III. WIND SYSTEM

3.4.1 Introduction

GRID-connected wind electricity generation is showing the highest rate of growth of any form of electricity generation, achieving global annual growth rates in the order of 20 - 25%. It is doubtful whether any other energy technology is growing, or has grown, at such a rate. Global installed capacity was 47.6 GW in the year 2004 and 58.9 GW in 2005. Wind power is increasingly being viewed as a mainstream electricity supply technology. Its attraction as an electricity supply source has fostered ambitious targets for wind power in many countries around the world. Wind power penetration levels have increased in electricity supply systems in a few countries in recent years; so have concerns about how to incorporate this significant amount of intermittent, uncontrolled and non-dispatchable generation without disrupting the finely-tuned balance that network systems demand. Grid integration issues are a challenge to the expansion of wind power in some countries. Measures such as aggregation of wind turbines, load and wind forecasting and simulation studies are expected to facilitate larger grid penetration of wind power.

3.4.2 Power from Wind

The power that can be captured from the wind with a wind energy converter with effective area $A_r$is given by

$$P = \frac{1}{2}\rho_{air} C_p A_r v_w^3$$

….(1)

Where pair is the air mass density [kg/m3], $V_w$is the wind speed and $C_p$is the so-called power coefficient which depends on the specific design of the wind converter and its orientation to the wind direction. Its theoretical maximum value is 16/27 = 0.593 (Betz limit). For a wind turbine with given blades it can be shown that the power coefficient $C_p$basically depends only on the tip speed ratio *l*, which equals the ratio of tip speed V_t[m/s] over wind speed V_w[m/s] and the so-called blade pitch angle *q* [deg]. This pitch angle is defined as the angle between the cord of the blade and the plane of the wind rotor. So, for a wind rotor with radius *r*, (1) can be rewritten as:

$$P = \frac{1}{2}\rho_{air}C_p(\lambda,\theta)\pi r^2 v_w^3 \quad .....(2)$$

As an example, Fig. shows the dependency of the power coefficient *Cp*on the tip speed ratio *l* and the blade pitch angle *q* for a specific blade. For this blade maximum energy capture from the wind is obtained for *q* =0 and *l* just above 6. To keep *Cp*at its optimal value for varying wind speed, the rotor speed should be proportional to the wind speed. In practice both constant *l* (variable speed) and constant speed operation is applied.

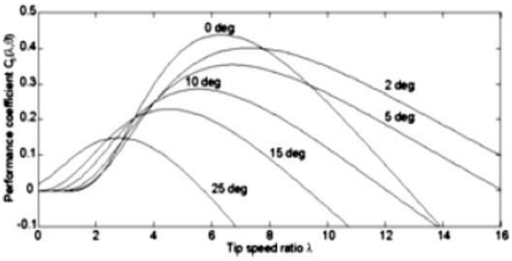

Fig: 3.8Power coefficient Cp as a function of tip speed ratio l and pitch angle q for a specific blade.

For on shore turbines, the blades are designed such that the optimal tip speed is limited to roughly 70 m/s. This is done because the blade tips because excessive acoustical noise at higher tip speeds. For offshore turbines, the noise does not play an important role, and higher speeds are used leading to slightly higher optimal values of *Cp*.The relation between wind speed and generated power is given by the power curve, as depicted in Fig. 3.9. The power curve can be calculated from eq(2) where the appropriate value of *l* and *q should* be applied. In the power curve, four operating regions can be distinguished, that apply both to constant speed and variable speed turbines:

1. No power generation due to the low energy content of the wind.
2. Less than rated power generation. In this region, optimal aerodynamic efficiency and energy capture is aimed at. The wind speed at the boundary of region 2 and 3 is called the rated wind speed and all variables with the subscript rated refer to design values at this wind speed.
3. Generation of rated power, because the energy content of the wind is enough. In this region, the aerodynamic efficiency must be reduced, because otherwise the electrical system would become overloaded.
4. No power generation. Because of high wind speeds the turbine is closed down to prevent damage.

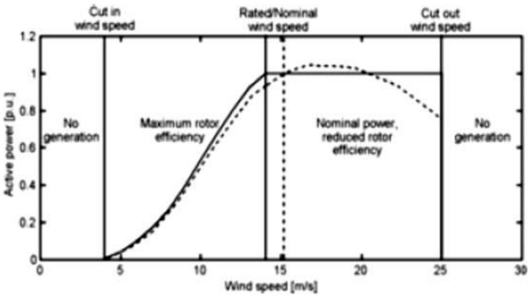

Fig: 3.9 typical power curve of a constant speed stall (dotted) and a variable speed pitch (solid) controlled wind turbine.

3.4.3. Aerodynamic Power control

The shaft power should be less than the available power from wind to prevent overloading of components. There are two main methods for limiting the aerodynamic efficiency in high wind speeds. With the first method one takes advantage of the aerodynamic stall effect. When the angle, at which the wind hits the blade ('angle of attack'), is gradually increased, then at a certain angle the airflow will no longer flow along the blade, but will become loose from the blade at the back side. Large eddy's will be formed that result in a drastic reduction of *Cp.*

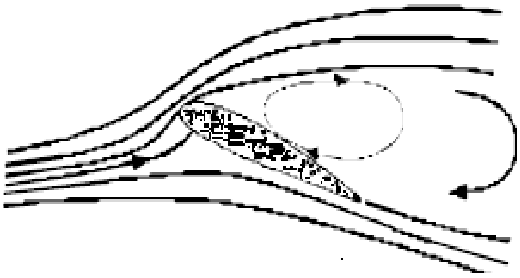

Fig.:3.10. Stalled flow around an aerofoil.

If a turbine is operated at constant speed and the wind speed increases, then automatically the angle of attack increases. At a certain wind speed the angle of attack will reach the value where stall occurs. Here it is assumed that the pitch angle *q* is not changed. With so-called stall controlled turbines the blade are designed such that the stall effect just starts at the rated wind speed. Due to the stall effect, the power is more or less constant above rated wind speed, as indicated by the dotted curve in Fig. 3.10. No active control systems are used to achieve this, which also implies that the blade does not need to be patchable.With variable speed (constant *l*) wind turbines the angle of attack is independent of the wind speed so that the stall effect does not occur. To reduce the power above the rated wind speed the blades are pitched towards the vane position by hydraulic or electric actuators resulting in a reduction of *Cp*. Above the rated wind speed the variable speed turbines are normally operated at constant speed, where power (so torque) is controlled by the pitch angle. This results in a flat power curve above the rated wind speed (solid line in Fig. 3.11). From above it will be obvious that stall control is mainly used with constant speed turbines and pitch control with variable speed wind turbines.

3.4.4. Energy yield

The annual energy yield *E* of a wind turbine depends on its power curve *P(vw)* and the probability density distribution function *u(vw)* of the wind speed at the turbine site:

$$E = \int_0^\infty P(v_w)\cdot u(v_w)\,dv_w \qquad \ldots(3)$$

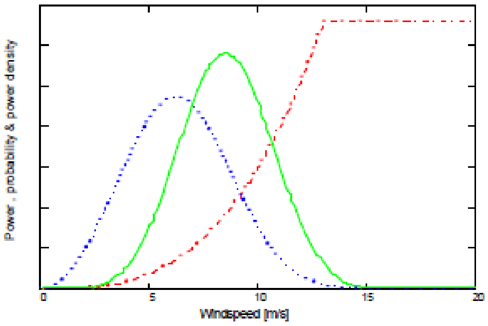

Fig: 3.11 Power P (red, dashed), probability density U (blue, dotted) and power density (green, solid) as a function of wind speed (arbitrary units).

3.4.5 ALTERNATIVES AND TRENDS

3.4.5.1 Alternative generator systems

- **Variable speed with squirrel cage induction generator**

A few manufacturers have produced variable-speed wind turbines with squirrel cage induction generators with a converter carrying the full power.Compared to the doubly-fed induction generator this system has the following advantages

(a) The generator is cheaper,
(b) The generator has no brushes,
(c) The system is often used as a standard industrial drive,
(d) It can be used both in 50 Hz and 60 Hz grids, and the following disadvantages,
(e) The losses in the converter are higher because all power is carried by the converter.

From the fact that this solution is known and rarely applied, it can be concluded that its disadvantages are more important than the advantages.

- **Variable speed with geared synchronous generator**

Recently, the Spanish manufacturer Made developed a geared wind turbine with a brushless synchronous generator and a full converter.Compared to the doubly-fed induction generator, this generator system has the following advantages

a) The generator has a better efficiency,
b) The generator is cheaper,
c) The generator can be brushless,
d) It can be used both in 50 Hz and 60 Hz grids, and the following disadvantages
e) Larger, more expensive converter (100% of rated power instead of 35%), and
f) The losses in the converter are higher because all power is carried by the converter.

3.4.5.2. Trends in geared generator systems

The first trend to be mentioned is the fact that in recent years, many wind turbine manufacturers changed from constant speed to variable speed systems for the higher power levels for reasons mentioned.The doubly -fed induction generator systems have been made suitable for grid fault ride-through. A next step might be than the turbine has to be made suitable to assist in the voltage and frequency (V&f) control of the grid, which is in theory possible, but should be implemented in practice.The generators used in geared wind turbines are more or less standard off-the-shelf electrical machines, so that major development steps were not necessary.

3.4.5.3. Trends in direct-drive generator systems

Most of the current direct-drive generators are electrically excited synchronous generators (Enercon, Lagerwey). Some manufacturers work on permanent-magnet synchronous generators (Zephyros, Jeumont, Vensys). Enercon and Lagerwey started developing direct-drive generators in the early nineties, when permanent magnets were too expensive. Although magnet prices dropped by roughly a factor of 10 over the past 10 years, Enercon seems to stick to it successful, well-known and proven solution.The advantages of permanent-magnet excitation when compared to electrical excitation are lower losses (no excitation losses), lower weight (roughly a factor 2 in active generator material) and lower cost. A disadvantage is that the excitation cannot be controlled. As early as in 1996, it was stated in that permanent-magnet generators were more attractive than electrically-excited synchronous generators. Since then, the permanent-magnet generator has only become more attractive due to the decreasing magnet prices.Direct-drive generators are not standard off-the-shelf machines. Therefore, it is worthwhile to study the use of alternative generator topologies which offer the possibilities of further weight and cost reduction.Axial flux generators as used by Jeumont generally are smaller, but also heavier and more expensive than radial flux machines. This is because in axial flux machines the force density introduced is not optimal for all radii, and because the radius where the force works is not everywhere maximum.The use of transverse flux generators has been investigated for application in wind turbines because in literature, very high force densities are claimed for this machine type. However, this high force density disappears when the machine has a large air gap, which generally is the case in large direct-drive generators. An advantage of transverse flux generators is the simple stator winding geometry, which offers possibilities to apply high voltage insulation.Disadvantages are the very low power factor and the complex construction, which may result in mechanical problems and audible noise. In the TFPM machine with toothed rotor proposed in , some rotor construction problems have been solved.

Wind power has the following advantages over the traditional power plants.

- Improving price competitiveness,
- Modular installation,
- Rapid construction,
- Complementary generation,
- Improved system reliability, and
- Non-polluting.

3.5 Mini-Hydro Power:

3.5.1. Introduction

Hydropower is energy from water sources such as the ocean, rivers and waterfalls. “Minihydro” means which can apply to sites ranging from a tiny scheme to electrify a single home, to a few hundred kilowatts for selling into the National Grid. Small-scale hydropower is one of the most cost-effective and reliable energy technologies to be considered for providing clean electricity generation. The key advantages of small hydro are:

- High efficiency (70 - 90%), by far the best of all energy technologies.
- High capacity factor (typically >50%)
- High level of predictability, varying with annual rainfall patterns
- Slow rate of change; the output power varies only gradually from day to day (not from minute to minute).
- A good correlation with demand i.e. output is maximum in winter
- It is a long-lasting and robust technology; systems can readily be engineered to last for 50 years or more.

It is also environmentally benign. Small hydro is in most cases “run-of-river”; in other words any dam or barrage is quite small, usually just a weir, and little or no water is stored. Therefore run-of-river installations do not have the same kinds of adverse effect on the local environment as large-scale hydro.

3.5.2. Hydro Power Basics:

3.5.2.1.Head and Flow

Hydraulic power can be captured wherever a flow of water falls from a higher level to a lower level. The vertical fall of the water, known as the “head”, is essential for hydropower generation; fast-flowing water on its own does not contain sufficient energy for useful power production except on a very large scale, such as offshore marine currents. Hence two quantities are required: a Flow Rate of water **Q**, and a Head **H**. It is generally better to have more head than more flow, since this keeps the equipment smaller. **The Gross Head** (H) is the maximum available vertical fall in the water, from the upstream level to the downstream level. The actual head seen by a turbine will be slightly less than the gross head due to losses incurred when transferring the water into and away from the machine. This reduced head is known as the Net Head. **Flow Rate (Q)** in the river is the volume of water passing per second, measured in m3/sec. For small schemes, the flow rate may also be expressed in litres/second or 1 m3/sec.

3.5.2.2. Power and Energy

Power is the energy converted per second, i.e. the rate of work being done, measured in watts (where 1watt = 1 Joule/sec. and 1 kilowatt = 1000 watts).In a hydro power plant, potential energy of the water is first converted to equivalent amount of kinetic energy. Thus, the height of the water is utilized to calculate its potential energy and this energy is converted to speed up the water at the intake of the turbine and is calculated by balancing these potential and kinetic energy of water.

Potential energy of water $E_p = m*g*H$

Capacity Factor is a ratio summarizing how hard a turbine is working, expressed as follows:

Capacity factor (%) = Energy generated per year (kWh/year) / {Installed capacity (kW) x 8760 hours/year}

Energy is the work done in a given time, measured in Joules. **Electricity** is a form of energy, but is generally expressed in its own units of kilowatt-hours (kWh) where 1 kWh = 3600 Joules and is the electricity supplied by 1 kW working for 1 hour. The annual energy output is then estimated using the Capacity Factor (CF) as follows:

Energy (kWh/year) = P (kW) × CF × 8760

3.5.3. Main Elements of a Hydro Power Scheme:

Main components of a small scale hydro power scheme can be summarized as follows:

- Water is taken from the river by diverting it through an intake at a weir.

- In medium or high-head installations water may first be carried horizontally to the forebay tank by a small canal.
- Before descending to the turbine, the water passes through a settling tank or 'forebay' in which the water is slowed down sufficiently for suspended particles to settle out.
- Forebay is usually protected by a rack of metal bars (a trash rack) which filters out waterborne debris.
- A pressure pipe, or 'penstock', conveys the water from the forebay to the turbine, which is enclosed in the powerhouse together with the generator and control equipment.
- After leaving the turbine, the water discharges down a 'tailrace' canal back into the river.

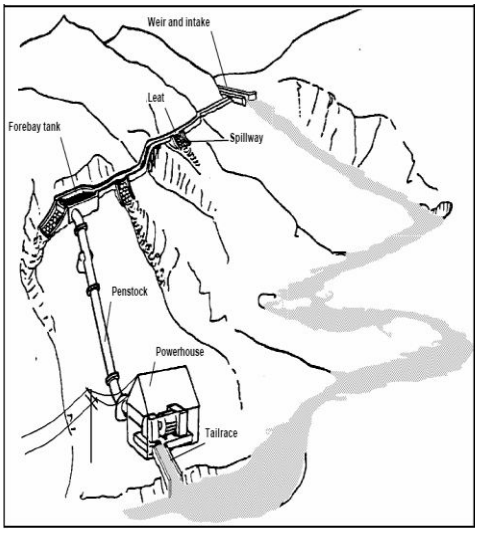

Figure 3.12: Main components of Hydro power Scheme

Measuring weirs

A flow measurement weir has a rectangular notch in it through which all the water in the stream flows. It is useful typically for flows in the region of 50-1000 l/s. The flow rate can be determined from a single reading of the difference in height between the upstream water level and the bottom of the notch. For reliable results, the crest of the weir must be kept 'sharp' and sediment must be prevented from accumulating behind the weir.

SIMULATION RESULTS

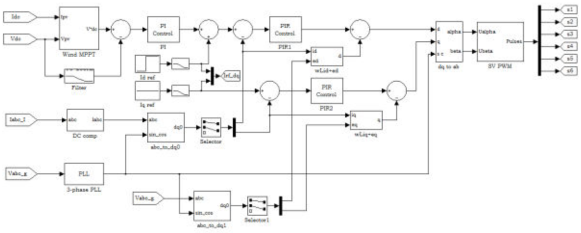

Fig. Control configuration with PLL

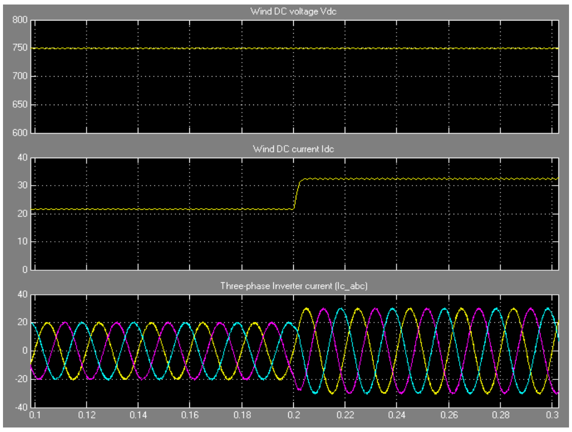

Fig..Wind DC voltge , Wind DC current and inverter output currents

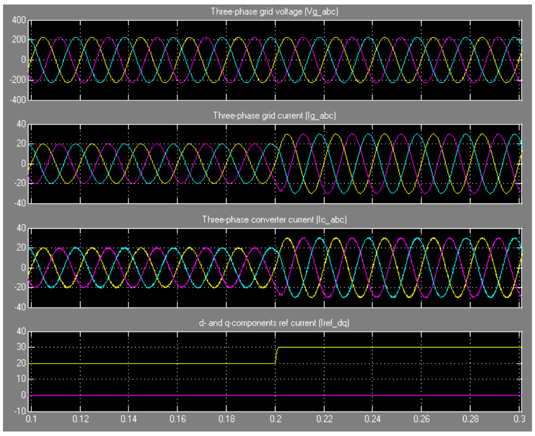

Fig.Grid voltge , grid current , inverter currents and ref dq comp currents

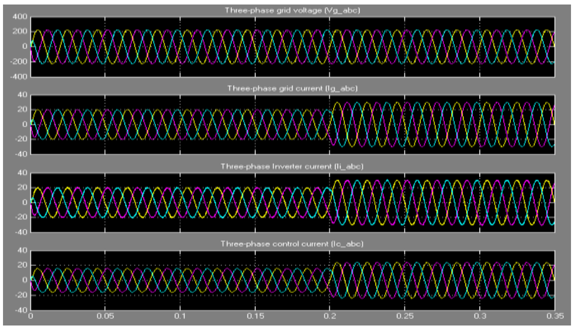

Fig. Grid voltge , grid current , inverter currents and contol currents

CONCLUSION

In this paper, Inverter control is a challenging part of designing the output stage of a type-4WT. In this project, traditional loop-shaping methods were compared to an *H*∞optimal design with focus on minimizing disturbance rejection for use in inner loop system current control schemes. The*H*∞design using notch filters tuned at the odd harmonic frequencies combined with approximate integral action showed a considerable improvement in performance concerning overshoot, control effort, and specific output disturbance rejection. Robust performance and stability were achieved with a uncertainty span equivalent to a collector system with one to multiple connected turbines.

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