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Impact of Renewable Energy Sources on Inertia and Frequency Response of Power Systems

(تأثير مصادر الطاقة المتجددة على القصور الذاتى و إستجابة التردد فى شبكات القوى الكهربية)

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KEYWORDS:
Power system stability, power system inertia, inertia constant estimation, virtual inertia.

الملخص: مع الإستخدام الكثيف و المتنامى لمصادر الطاقة المتجددة، فإنها تؤثر على ديناميكية و إتزان شبكات القوى الكهربية. و هذا البحث يدرس تأثير هذه المصادر على ديناميكية شبكات القوى الكهربية لا سيما من خلال تسببها فى تقليل القصور الذاتى للشبكة. و بالتالى تأثيرها على استجابة و اتزان تردد الشبكة. و يقدم البحث تحليل لتأثير القصور الذاتى على ديناميكية تردد الشبكة، و يعطى طريقة لقياس القصور الذاتى للشبكة الكهربيه من خلال القراءات اللحظية و تطبيق ذلك على شبكة بسيطة. و أخيرا يقدم البحث مجموعة من الحلول المقترحة لتحسين ديناميكية شبكات القوى الكهربية مع الإستخدام المتزايد لمصادر الطاقة المتجددة.

***Abstract*— With its extensive and growing use in power systems, renewable energy sources (RES) affect power system dynamics and stability. This paper presents the impact of renewable energy sources on power system dynamics, especially through their effect on reducing the system inertia. Thus, affecting power system frequency response and stability. An analysis of the effect of inertia on system frequency dynamics is presented. Also, the possibility of determining the system inertia through online measurements is discussed and illustrated with a double-bus case study. Finally some suggested solutions for enhancing power system dynamics with high penetration levels of renewables are presented.**

I. INTRODUCTION

POWER system stability may be defined as the ability of power system to maintain in equilibrium state and regain an acceptable state of equilibrium after being subjected to a disturbance. One important measure of power system stability is the grid frequency. It should be kept within acceptable limits of 0.5% of nominal value [1]. Power system frequency is dependent upon active power balance. Any change in system demand with respect to system generation cause a change in speed, acceleration or deceleration, of moving parts in the system [1], [2]. As the speed of synchronous generators, the main generation units in conventional power systems, is directly coupled to system frequency, an instantaneous change in system frequency occurs [1], [3].

Following a frequency event, the stored kinetic energy in the rotating parts of conventional generators is then directly released or absorbed. When system demand increases, moving parts of the system will decelerate and release some energy to the system, limiting the frequency deviation. On the other hand, when system demand decreases, moving parts of the system will accelerate and absorb some energy from the system, also limiting the frequency deviation. Finally, the

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inertia of conventional generators minimizes the change of system frequency following any changes in loading levels on the system. This enhances the system initial frequency response and allows more time to other frequency controllers to respond. Generally the system inertia is an immediate and self-initiated means of frequency support. It starts acting at the moment a frequency event takes place. Usually it is the only frequency support means during first swings following a disturbance. After that, primary and secondary control of generators and other controlling devices in the system will start to operate besides the system inertia.

When the total inertia in the system is reduced, frequency deviation increases. Thus the system becomes more vulnerable to stability problems, especially from the disturbance instant to the instant when primary and secondary control start to operate. Then the time available for these controllers to operate, to avoid frequency instability, becomes less. The increased, actually mushrooming, rate of utilizing renewable energy generators, such as wind turbines (WT) and solar photovoltaic (PV) units, is a major cause of system inertia reduction. This is due to the fact that almost all power from these sources enters the system through power electronic devices; this isolates the mechanical parts and the stored energy, if any, from supporting the system frequency.

The rest of this paper is organised as follows: section II discusses different stages of frequency control on conventional power systems. In section III, the impact of RES on power system dynamics and frequency response is presented. An estimation procedure of system inertia is introduced in section IV. In section V, a simple case study is used to verify the estimation procedure. Some methods for enhancing system stability and frequency response are introduced in section VI. Finally, the conclusions of this paper are presented.

II. FREQUENCY CONTROL STAGES

Frequency control in traditional power systems, that utilize conventional synchronous generators, can be divided into three stages. The first stage represents the inertial response of these units. The second stage includes the primary and secondary control operations of synchronous generators. The third stage is manual and usually called tertiary frequency control.

A. System Inertia

Conventional generators store kinetic energy in their rotating parts. This stored energy is directly released or absorbed following a disturbance, enhancing the system initial frequency response. When a generation-demand imbalance occurs, there would be an imbalance between torques acting on the generators' rotors causing acceleration or deceleration. The stored kinetic energy in a generator is usually defined as a ratio of its VA rating, called inertia constant (H). It can be defined as the time, in seconds, required for a machine operating at its rated output power and speed to replace its kinetic energy. Swing equation, given in 1, describes the relation between the power imbalance, inertia constant, and rate of change of frequency.

$$\frac{2\mathrm{H}}{\omega_0}\frac{\mathrm{d}\omega_\mathrm{m}}{\mathrm{dt}} = \mathrm{P_m}\text{-}\mathrm{P_e}\text{-}\mathrm{k_d}\,\Delta\omega \tag{1}$$

The damping factor K_d is usually neglected for short time studies such as the short time after disturbances. Thus we get the following simple form of 1:

$$\frac{2H}{\omega_0}\frac{d\omega_m}{dt} = P_m - P_e = \Delta P \tag{2}$$

Where ω_0 and ω_m are the rated speed and mechanical speed of the machine in [rad/sec] respectively. P_m and P_e are the mechanical and electrical powers of the machine in [pu] respectively. H is the inertia constant in [sec] and it equals the stored kinetic energy divided by given machine VA .

It is clear in 2 that for a specific power imbalance, the rate of change of frequency (ROCOF) is reduced with increasing system inertia. This avoids mal-operation of ROCOF relays installed in the system against islanding processes. ROCOF relays depend on the fact that when islanding occurs, there would be high imbalance between local generation and demand causing high ROCOF. This would exceed the relays set value causing them to disconnect most of the installed Distributed generation (DG) in the system for safety reasons [4]. High system inertia, in addition to reducing ROCOF for load violations, allows more time for synchronous machines and other controllers to react[3],[4]. This reduces the maximum value of frequency change Δf.

B. Primary and Secondary Control Systems

Conventional power plants are equipped with two automatic control systems; primary and secondary frequency control systems. Each unit is equipped with a primary control system, but some of them are not equipped with secondary control system [1].

Primary control represents the governor action which reacts directly for any deviation in system frequency. It is provided within few seconds, usually 30 s, after the deviation [5]. The governor reduces the frequency deviation that will be reached after a frequency event, but not to zero. This keeps the frequency within acceptable limits until the secondary control system operates.

Secondary frequency control system, which utilizes a PI controller, is performed only in the area of disturbance [1], [6]. It aims to return to system nominal frequency. It starts after approximately 30 s from the deviation [5] for a timeframe of minutes [6].

C. Tertiary Frequency Control

In tertiary frequency control stage, the dispatched generating units are changed manually, within tens of minutes to few hours after a disturbance. This manual control stage aims to restore the primary and secondary reserves [6].

III. IMPACT OF RENEWABLE ENERGY SOURCES ON SYSTEM INERTIA AND STABILITY

The system inertia has many remarkable advantages on power system stability as discussed. When, for any reason, this inertia is reduced, these benefits would be lost. Consequently, causing many problems in system stability and operation.

Through last decades, the global trend was to replace conventional power plants with RES and feeding growing loads with renewable. This is to reduce environmental impacts of fossil fuels and to ensure security of energy supply [3]. Future plans include higher penetration levels of renewables. RES, such as wind turbines and solar PV plants, are different from synchronous generators in many aspects. Most of these sources do not contribute to system inertia, thus reducing the effective inertia in the system. Also, operation policies deals with these sources as negative demand in the grid. Thus these sources do not contribute to the total system reserve. Finally, these sources have their output depends on weather conditions and control strategies. Varying weather conditions provide variable output from these sources. Wind plants, which store inertia in their generators and blades, are usually controlled for maximum power output. This maximum efficiency control strategy keeps the plant inertia whatever the frequency event on the grid.

Increased penetration of RES, reduces the effective system inertia more and more. Systems with low inertia would lose many benefits. For a specific power imbalance, the frequency deviation would be larger and faster than that in a conventional power system. The fast change in frequency (high ROCOF) may exceeds the set point of ROCOF relays, installed in the system. This case is seen by ROCOF relays as an islanding state and these relays would operate. Thus many DGs would be disconnected from the grid. This may increase the initial imbalance causing more frequency deviation and in some cases, real islanding may occur. This may finally cause blackout to a large portion of the system, or may be the whole system. If it is not the case, the frequency deviation is more and the time available for primary and secondary control systems, to regain nominal system frequency f0, is less.

The worst case is when penetration levels are high enough that the system may be represented as an inertia-less system. Unlike conventional systems, inertia-less system is less capable of damping small signal disturbances such as load changes. For a satisfactory generation-demand imbalance, the system frequency changes more rabidly and almost will exceed safe minimum/maximum values. Over speed or under frequency protection systems will disconnect some conventional units, and ROCOF relays will disconnect some DGs. Finally, many generating units are disconnected and blackout of the system occurs. Generally, the less inertia of the system, the more weak it is. System inertia is one of the most important features for its stability and continuity of supplying energy. Increased utilization of RES should then be equipped with some frequency support methods.

IV. ESTIMATION OF SYSTEM INERTIA

With high levels of RES, inertia of power systems is variable. Dispatching schemes give priority to RES, but their output is variable. Thus the online conventional generators is variable also with RES changes, besides changes in load profiles. The amount of inertia at any time is then important for determining how strong the system against any disturbance is. Many operator decisions may depend on system inertia in such cases. As a result, estimation of system inertia is important for making proper actions that ensures the system stability and security.

Many researches had been introduced for estimating inertia constant with different calculating methodologies and purposes. In [7], a procedure for estimating the inertia constant M (=2H) of a power system and total on-line capacity of spinning-reserve support generators, using transients of the frequency measured at an event is presented. A polynomial approximation with respect to time is applied, and the idea of average system frequency is assumed in estimating the capacity of the generators. The work in [8] evaluates the relationship of system inertia to total load, which is used to model system response to load curtailment programs in power system simulations. The inertia of induction generators based wind turbines is estimated in [9]. These researches have introduced good estimation of system inertia, but without considering the influence of the nature/size of the disturbance or the properties of the network [2]. The work in [2] introduces an estimation procedure for single and multi-machine systems and considers some factors that affect the estimation results.

A beneficial procedure for estimating power system inertia depending upon measured system values during disturbances using swing equation is produced as follows: Rearranging the simplified swing equation given in 2 to get the inertia constant; we obtain the following equation

$$\mathrm{H} = \frac{\mathrm{P_m} - \mathrm{P_e}}{2\,\frac{d\omega_m}{\mathrm{dt}}} \tag{3}$$

This equation is valid for any synchronous machine in the system. At steady state, the mechanical power equals electrical power output, thus when a disturbance occurs the mechanical power is equal to electrical power just before the disturbance $P_m = P_{e0}$. Also the machine speed can be replaced by system frequency then we get:

$$\mathrm{H} = 0.5\ \mathrm{f_0}\ \frac{\mathrm{P_{e0}} - \mathrm{P_e}}{\frac{\mathrm{df}}{\mathrm{dt}}} \tag{4}$$

Given the instantaneous values of output power and system frequency during a disturbance, inertia constant can be estimated accurately from 4. PMU devices installed at the measuring bus can easily give the required samples of voltage current and frequency. Errors in measured values from PMUs appear in estimation result.

V. CASE STUDY

A simple single machine-infinite bus system, as shown in Fig.1, is used for verifying the calculation procedure. The system is loaded with load 1. When load 2 is suddenly applied to the system, the system frequency changes and machine inertia can be estimated during the interval of frequency change. In this model, the parameters of the synchronous generator used are presented in table I.

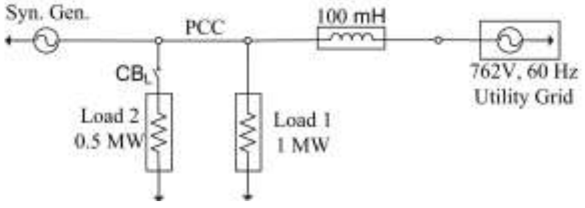
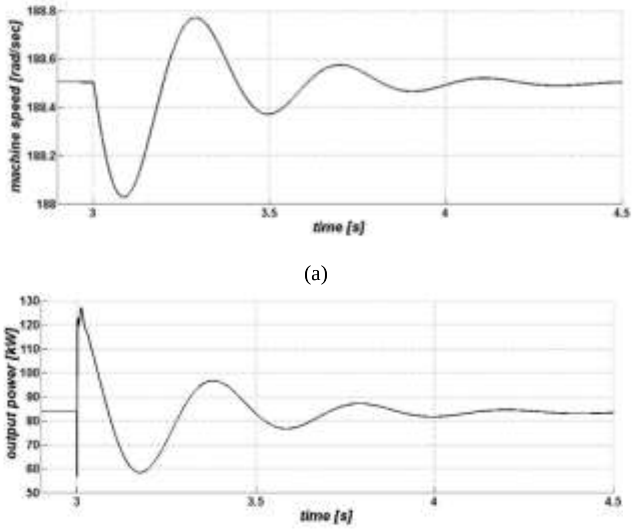


Fig. 1. Model of the system used for estimation procedure.

TABLE I
PARAMETERS OF GENERATOR USED IN THE SYSTEM UNDER STUDY.

Nominal voltage	762 V
Nominal power	111.9 kW
Nominal frequency	60 Hz
Machine Inertia	24.9 kg.m^2

Matlab/Simulink software is used for modelling and calculation of the machine inertia. Load 2 is suddenly applied at time = 3 s. The machine speed and output power due to this frequency event are shown in Fig.2 (a) and (b) respectively.



(a)

(b)

Fig. 2. Machine angular speed [rad/s] and output power [kW] after the disturbance

Machine output power and speed are sampled with a time interval of 10 µs. These samples are used for the estimation procedure using 4. Calculation starts at the instant of disturbance. In this simple model, calculations are made along the change interval. For actual data, calculation are only true during short time interval after the disturbance; usually during the first or second swing. The error of the results is computed from the following equation.

$$error = \frac{J_{true} - J_{est}}{J_{true}} * 100 \qquad (5)$$

Where J_{true} and J_{est} are the true value and estimated value of machine inertia in [kg.m2] respectively. The average error is computed to be 6.4362 % giving an estimated value of J = 23.2974[kg.m2]. Extreme high error values are noted, as expected, when the difference between machine output power is approximately equal to its mechanical power. Fig. 3 shows the percentage error of each estimated value of machine inertia. Removing these values we get an average error of 0.8710 % and the value of estimated machine inertia is 24.6831 [kg.m2].

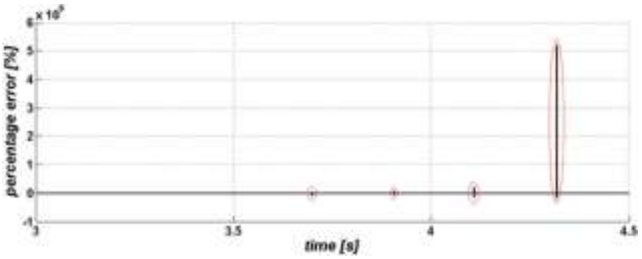


Fig. 3. Percentage error vs. time during estimation interval.

Obtained results are optimistic. More realistic results that may be obtained from similar real case should be limited with the interval during which swing equation is true as discussed in section II in this paper. Assuming primary control, if exists, would operate after 0.5 s following the disturbance we get the following results: estimated machine inertia equals 23.1808 [kg.m2]. The error in estimated value is increased to 6.9043%.

VI. POWER SYSTEM STABILITY SUPPORT METHODS

The problem of reduced system inertia is growing with increased penetration of RES. This ensures the idea that the inertia of global power systems, in the near future, will be very low as a result of high levels of renewable enrgy generation as planned. This leads to the importance of substituting for that inertia to, at least, keep system stability at current level. Enhancing system dynamics may be performed using two levels. The first may be changing operation policies of already existing devices in the system to make a larger contribution in system inertia. The second level includes adding new devices that support system frequency and dynamics during disturbances.

A. Modified Operation of Existing System Elements

One aspect of the problem is that replacing conventional generators with inertia-less ones reduces the number of units that contribute to the system inertia. For a given load, a specific number of conventional generators are scheduled for feeding it. If the scheduling process contains RES such as WTs and solar PV units, they have a priority of operation. Thus some units are curtailed and some are shut down as they exceeds their minimum loading levels. The problem comes from these offline units. A possible solution is to reduce the minimum loading levels of conventional units [3]. This allows more units to be online but with non-preferred loading levels. The same may be achieved by lowering maximum loading on each units. This also keeps more units online without exceeding minimum loading levels. Both solutions will improve the system inertia, but with inefficient operating conditions of many units in the system.

For these units that may still offline for longer time according to load profiles. It may be better to operate them, if possible, as synchronous condensers than shutting them down. This avoids the costs of start-up and shut down of units. Also they may be used for frequency support in addition to existing synchronous condensers in the system as follows. Synchronous condensers are compensating devices usually used in power systems for reactive power and voltage control. They are synchronous motors operating at no load. They are used to generate or absorb reactive power from the system for enhancing power system voltage [1]. Being synchronous machine, their speed is directly coupled to system frequency and they store kinetic energy in their rotors. Thus they can be used to increase the inertia of the system and improving ROCOF following a frequency event. The added inertia by them can be further increased by adding, if possible, flywheels to their rotor shafts [3].

B. Virtual Inertias for F3requency Support

Wind turbines, by nature, contribute to stored kinetic energy and have inertia constant that varies between 2–5 sec [4],[11],[12]. Being decoupled from system frequency through power electronic devices, control actions should be taken to release WT inertia during a frequency event. Thus, it can be treated as a virtual inertia. The virtual inertia of WTs vary from conventional inertia in two major points; WTs inertia varies with varying wind speed and can be controlled to deliver more energy than conventional generators when needed [4].

Many other methods can be used as virtual inertias for frequency support in power system. WT and PV plants can be supplied with a storage system such as batteries and capacitors [13], [14]. Charging and discharging processes of these devices would be performed according to operating state of the system. Another method is to keep some reserve from RES by curtailing PV or WTs output. This may be uneconomic and go against operation policies. But their reserve can be released in cases of frequency decrease events. This aids primary and secondary control systems of conventional generators to support system frequency for longer time [4]. Finally, Flywheels can be used along the system specially areas with low inertia. Flywheels are similar to synchronous machines; store kinetic energy in their rotating mass. This energy can be released or absorbed for system frequency support during power imbalance and other disturbances that changes the system frequency

VII. CONCLUSION

The measurements of system inertia and its impact on frequency dynamics have been discussed and illustrated via simple yet informative test case. Estimations have been performed depending on online measurements and the error of estimation was calculated. It was found that estimation error is lower when calculations were performed over the total period of frequency change, less than 1% for the presented case study. This error increased, to approximately 7%, when the calculations were performed during first swing only. For an actual system, the errors is expected to be higher due to errors in actual measurements.

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