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Abstract—Knowledge of on-line inertia in power systems with high and increasing levels of wind penetration is becoming more important for power system operators. In this paper, the basis of a real-time stored energy estimator is developed, which accounts for the inertia contribution from loads as well as generators in the system. By creating a simplified first order model of the system, power and frequency signals recorded are utilized to estimate real-time feeder stored energy by use of a linear least-squares estimator. The capability of the proposed estimator is investigated by application on a test system. The estimation error is analysed in respect of data resolution and feeder contributions to stored energy. Discussion on the requirements for applications within power systems and the communication configuration are also presented.

Keywords- Stored energy, inertia, real-time, least-squares estimation

I. INTRODUCTION

Power system operators in countries with high wind penetration levels are experiencing a challenging situation regarding system frequency stability [1]. After a generator or large infeed outage on the power system, the frequency falls at a rate which is proportional to the on-line system inertia at the time of the trip. This rate of change of frequency affects the design of primary reserve schemes, its activation speed, and backup frequency recovery plans [2]. Knowledge of the system on-line inertia is crucial for operating the system in a secure state; otherwise, conservative safety margins must be introduced. The system overall inertia refers to the sum of all rotating masses in the system (or precisely, all elements in the system which show power sensitivity to frequency deviations), i.e. generating units, fixed-speed wind turbines, motors and non-linear loads. Traditionally, the mass of on-line synchronous generators was so large that the overall system inertia could be conveniently defined by the sum of all on-line generators’ inertia at any time and the contribution from load was seen as an additional buffer. However, with the vast increase in the level of renewable generation, wind power in particular, in smaller power systems and the consequent displacement of large synchronous generators by large numbers of modern wind turbines, coupled with the trend for more DC interconnectors, the level of inertia in such systems has decreased. Moreover, the variation in renewable production and demand, results in a more varying inertia in systems with high wind penetration. Power system operators are then required to have an accurate view of all sources of inertia. Subsequently, system operators may decide to alter system dispatches, connect other sources of inertia such as synchronous condensers or incentivise wind farms to contribute an inertial response [3-5].

An observation of system inertia can only be gained if the masses’ speed changes. This speed change can be a large signal due to generation outages, or a small signal due to load variations. The overall system inertia concept has been investigated over many years, mainly using the concept of large changes in frequency after generation outages [6-9]. The overall system on-line inertia is then extracted through knowing the power lost and the extent of the frequency excursion. Although the inertia estimated by these methods is straightforward and precise, they are limited to the time of individual faults. With inertia varying with time, there isn’t sufficient event data available to draw a general picture of the inertial variation over long periods. In this paper, the concept of natural system load changes in a feeder is used to estimate the stored energy contribution of the feeder, which is a similar concept to inertia, referring to the kinetic energy of all rotating masses in the system. All load feeders are assumed to have a composite load model consisting of an equivalent induction machine and constant power load. Stored energy estimation is achieved using a linear least-squares estimator (LLSE) which is supplied with the feeder’s power and bus frequency. The inertia of the feeder is updated as soon as a quantifiable change in the feeder’s power is detected. Method performance with regard to load changes, feeder contribution to stored energy and data resolution is also investigated. It is shown that the proposed estimator is capable of extracting an inertial estimate with reasonable accuracy, so long as the system inertia stays large enough with respect to the feeder’s inertia and data resolution is sufficient. Data recording and communication configurations are also discussed.

The remainder of this paper is organized as follows. In Section II the principle of modelling and least-squares stored energy estimation is presented. Section III discusses the results of the test system application. Section IV discusses the precision and implementation, while Section V concludes this paper.
II. LOAD POINT INERTIA ESTIMATION

A. System and Load Models

The total system inertia in a power system includes the synchronous generator inertia from large power plants as well as the inertial contribution from sources which are connected to the system via feeders but whose contribution to system inertia is unknown. Examples of such feeders are composite load feeders, large industrial feeders, or even wind farms. The total synchronous inertia available from large power plants should be known. The contribution from other sources of inertia, however, may not since details of the loads and generation are usually unknown on a feeder [10]. However, the stored energy in the rotating masses in a specific load feeder may be calculated if a small change in load occurs. Fortunately, load variations occur all the time which makes it possible to extract informative data on the feeder contribution to system stored energy if measurements are available at the feeder. Fig. 1 shows a typical power system configuration and a branch which may consist of motors, small generating units or non-linear loads which may contribute to the system overall inertia. At the border bus BB, we can assume that two masses (representing stored energy) are connected to each other via springs (representing energy transfer paths). If the mass representing the system is large as compared to the mass representing the feeder, the feeder mass will oscillate against a large mass after a change in power. Due to the large mass of the system, it can be assumed invariant during small mass oscillations, i.e. an infinite bus. The resulting small-mass oscillation against an infinite bus can be tracked in the feeder’s active power and bus frequency. Going forward with this concept, in Fig. 1(a), a composite load consisting of an equivalent induction machine and constant power load is shown. It is desired to extract the inertial value using only the measured active (P) and reactive (Q) power and the system frequency (f_s) at BB. Fig. 1(b) depicts the equivalent circuit of the system, which is modelled at BB by the well-known voltage behind impedance concept, and a constant load is also included in the equivalent.

![Figure 1. Power system equivalent.](image)

The fundamental frequency-power equation of the equivalent machine, assuming the machine speed remains near nominal after load changes, is [11]:

\[
\frac{2E_s}{f_s} \frac{df_M}{dt} + \left[ \frac{16\pi^2 f_s}{p^2} \right] D_d \cdot f_M + P_{\text{Mech}} = P_M
\]

where \(f_M\) is the machine frequency deviation from nominal (Hz), \(P_M\) is the machine absorbed active power from the network (MW), \(P_{\text{Mech}}\) is the machine load power (MW), \(f_s\) is the nominal frequency (Hz), \(E_s = H\cdot S_p\) is the stored energy of the machine rotor mass (MWs), \(H\) is the inertia constant (s), \(S_p\) is the nominal apparent power of the machine (MVA), \(D_d\) is the damping torque coefficient (MJ/s) and \(p\) is the number of poles. In Fig. 1(a), the measured power at the feeder is:

\[
P = P_M + P_L
\]

The load power varies with the local voltage and frequency. Considering small changes in load, the voltage variation can be assumed to be small around nominal. Thus, (1) and (2) can be coupled to obtain the measured power at the feeder. Keeping in mind that the feeder contribution to system stored energy is assumed to be small, the angle of the system voltage in Fig. 1(b) will remain constant after a small load variation. The frequency at bus BB is related to the voltage by the following equations:

\[
\omega_h = \theta = \text{Im}\left\{ \frac{\ddot{V}}{V} \right\}
\]

\[
\ddot{V} = \ddot{V}^\|^\theta = \frac{Z_M E_{ST} + Z_{ST} E_M}{Z_M + Z_{ST}}
\]

where \(\omega_h = 2\pi f_h\) is the angular velocity measured at BB, \(f_h\) is the frequency at BB, \(V\) is the voltage vector at BB and \(\theta\) is the BB voltage angle. \(Z_M\) is the machine transient impedance, \(E_M\) is the voltage vector behind the transient impedance of the machine, \(Z_{ST}\) is the Thévenin impedance as seen from bus BB, and \(E_{ST}\) is the Thévenin voltage vector according to Fig. 1(b). The dot operator indicates the derivative with respect to time. The equivalent induction machine of Fig. 1 can be represented by a transient reactance and a transient voltage source. The angle and magnitude of the voltage behind the transient reactance in this model is mutually coupled with the machine speed by a system of differential equations [10]. To create a simplified relation between the equivalent machine speed and border bus frequency, the following are assumed:

- Voltage across the system will remain near nominal after changes in load
- System equivalent angle is essentially constant during small load changes
- Machine transient voltage angle variation is small after small load changes in the feeder
- Equivalent system resistance and reactance are evenly distributed, i.e. \(X_{ST}/R_{ST} = X_M/R_M\)

Applying the above to (1) and (2), coupled with the machine differential equation governing machine slip and transient voltage, the following approximation is made:

\[
\frac{\ddot{\theta}}{2\pi} = f_h = \frac{Z_{ST}}{Z_{ST} + Z_M}(f_M) = K_{ST}(f_M)
\]

We can call the dimensionless variable, \(K_{ST}\), the impact coefficient which defines to what extent inertia related oscillations can be observed in the border bus frequency. It is worth mentioning that the above equation is only valid when applying the above assumptions, a small contribution
of feeder stored energy in particular. Also, \( Z_{ST} \) represents the system and load impedance, where:

\[
Z_{ST} = \frac{Z_s Z_f}{Z_s + Z_f}
\]

(6)

\[
Z_L = \frac{|V|^2}{P - jQ}
\]

(7)

\( Z_s \) is the system impedance as seen from BB, and can be estimated by the transformers’ impedance voltage connecting BB to the remaining system. To complete the variable set, we need to know the transient reactance of the equivalent machine. After a change in feeder power which is large enough to excite the rotor circuit of the equivalent machine, small oscillations will occur in machine power for a short period of time. These oscillations can be tracked on the feeder’s power. Subsequently, there is a convenient way to extract the transient reactance of the equivalent induction machine. Finding the best parameter set to satisfy the following equation, we can extract the power oscillation magnitude of the feeder’s power against the system:

\[
\Delta P = \Delta P_M e^{-\frac{t}{T}} \cos(2\pi f_{osc} t + \phi)
\]

(8)

where the parameter set \( \{\Delta P_M, T, f_{osc}, \phi\} \) represent the oscillation characteristics of the feeder against the system. The oscillation magnitude is a function of the transient reactance of the equivalent machine:

\[
\Delta P_M = \frac{2|V|^2 \Delta V}{X_M^2} = \frac{\Delta Q}{X_M} \sqrt{P^2 + Q^2}
\]

(9)

where \( X_M \) is the equivalent machine transient reactance, which is assumed to represent the machine \( Z_M \) in Fig. 1(b). By combining (5) to (9), the impact coefficient \( K_{ST} \) is calculated. It just remains to rewrite (1) to construct the following fundamental equation:

\[
\frac{2E_s}{f_s} \frac{df_s}{dt} + \frac{16\pi^2 f_s}{p^2 \cdot K_{ST}} D_d f_b + P_b = P
\]

(10)

where \( P_b \) is the sum of all unknown power consumption, i.e. the load power and mechanical power of Fig. 1. By using a monitoring system to track changes in feeder power, the frequency, \( f_s \), and active power, \( P \), time variation will be available. It is possible to create a real-time inertia estimator when the optimal set of parameters satisfying (10) is extracted. A linear least-squares estimator is proposed to accomplish this task, which is explained in the next section.

B. Linear Least-squares Estimator

Although there are many examples of analytical methods for parameter estimation and modelling in power systems [12-13], measurement based system identification is one of the most applied methods in power system modelling. Least-squares estimation, in linear and non-linear formats, is generally applied in such studies [5-9, 14-15]. Addressing the load point inertia estimation problem, let’s assume that power and frequency \( \{P_t \text{ and } f_0\} \) are measured at time zero. After taking \( n \) samples of the above signals, measurement vectors over a process window are as follows:

\[
\bar{t}_{x1} = [t_1, t_2, \cdots, t_i, \cdots, t_n]^T
\]

(11)

\[
\bar{P}_{x1} = [P_1, P_2, \cdots, P_i, \cdots, P_n]^T
\]

(12)

\[
\bar{F}_{x1} = [F_1, F_2, \cdots, F_i, \cdots, F_n]^T
\]

(13)

By applying (10) to the measured samples, we will have \( n \) linear equations defining the system under identification. In matrix form:

\[
\bar{M}_{(n \times 1)} \bar{X}_{(n \times 1)} = \bar{U}_{(n \times 1)}
\]

(14)

where \( \bar{M} \) is the state matrix, \( \bar{X} = [E_s, D_d, P_b]^T \) is the vector of unknowns and \( \bar{U} \) is the vector of inputs. The state matrix and inputs vector can be constructed as follows:

\[
\bar{M}_{(n \times 1)} = \begin{bmatrix} M_1 & M_2 & M_3 
\end{bmatrix}
\]

(15)

\[
\bar{M}_{(1 \times n)} = \bar{M}_{(n \times 1)} = \frac{2}{f_s K_{ST}} \Delta \bar{F}_{(n \times 1)} / \Delta \bar{t}_{(n \times 1)}
\]

(16)

\[
\bar{M}_{2(n \times 1)} = \frac{16\pi^2 f_s}{p^2 K_{ST}} \bar{F}_{(n \times 1)}
\]

(17)

\[
\bar{M}_{3(n \times 1)} = [1]_{(1 \times 1)}
\]

(18)

\[
\bar{U}_{(n \times 1)} = \Delta \bar{P}_{(n \times 1)}
\]

(19)

Where .\( / \) stands for element-wise division and \([1]_{(1 \times 1)}\) is a column vector with \( n \) elements set to 1. The vector difference for an arbitrary vector \( R_{(n}) \) (i.e. \( P \) or \( f \)) is defined as follows:

\[
\Delta R_{(n)} = [\Delta r_1, \Delta r_2, \cdots, \Delta r_i, \cdots, \Delta r_n]
\]

(20)

\[
\Delta r_i = r_i - r_{i-1} \quad i = 1, 2, \cdots, n
\]

(21)

The number of measurements \( n \) over time is much bigger than 3, thus (14) does not have an explicit solution. One approach is to determine the answer which provides the lowest possible mean square error between the measured input vector \( \bar{U} \) and \( \bar{U} = \bar{M} \times \bar{X} \), which is the estimated vector. Assuming that the errors are independent and identically distributed with zero mean and unity variance, the following LLSE solution is obtained [16]:

\[
\bar{X} = [E_s, D_d, P_b]^T = \left[\bar{M}^T \bar{M}\right]^{-1} \bar{M}^T \bar{U}
\]

(22)

The above solution gives rise to an estimate of the system stored energy, damping and unknown power. When measurement \( n+1 \) is available, (11) to (13) can be updated by moving the processing window one step forward. Thus, vector \( \bar{X} \) will be updated over time. It is important to note that, returning to (8), the oscillation of the small inertia of the feeder against the system will damp finally to zero, which means that \( E_s(t) \) i.e. \( \bar{X}(1) \) extracts the stored energy for a period which is proportional to the oscillation time constant and after that time decays to zero. In order to create a quantity to track the stored energy in the feeder,
\( E_s(t) \) is further processed by applying the following integrator filter:

\[
\hat{E}_s(t) = \frac{1}{T_{\text{est}}} \int_0^t E_s(\sigma) \, d\sigma \tag{23}
\]

\[
\hat{D}_s(t) = \frac{1}{T_{\text{est}}} \int_0^t D_s(\sigma) \, d\sigma \tag{24}
\]

where \( T_{\text{est}} \) is the overall period that the estimator provides non-zero values after a load change. It should be noted that the above equation also incorporates a low pass filter which further smoothes the results. Returning to (16), it implicitly implies that noise in the frequency measurement will be amplified which requires some form of low pass filtering to eliminate high frequency noise. While (23) and (24) cope well with stored energy and damping, the estimated power signal is fed into a standard low-pass filter. The estimator output will be discussed further in Section III where the proposed estimator is applied to a test system.

### III. TEST SYSTEM APPLICATION

The proposed estimator in Section II is applied to a test system shown in Fig. 2, whereby a radial load feeder is assumed to be connected to the system by a step-down transformer. Three substations are connected to the feeder, where constant power and induction machines are connected. Of course, the motor loads could also represent wind turbines. By varying the loads connected to the downstream substations, the stored energy in the feeder is changed. Data related to this system is summarised in the Appendix.

![Figure 2. Test system for stored energy estimation.](image)

Fig. 3 shows the estimated stored energy and raw LSSE output \( \hat{E}_s \) and \( E_s \) for a simulation case when a 1% step is applied to the feeder load at time 0 s. Immediately after the load step, there is a sharp change in \( E_s \) which is due to fast changes in the power signal. However, incorporating a time delay which is proportional to the measurement vector length \( n \), the LSSE output matches the stored energy in the system. The estimator remains constant for a short period up to the time when the power signal oscillation is damped.

![Figure 3. Estimated stored energy, LLSE output (\( \hat{E}_s \)) and signal after filtering (\( \hat{E}_s \)).](image)

The filtered estimator output, \( \hat{E}_s \), as shown in Fig. 3, creates a smooth signal which follows the feeder contribution in stored energy. The same filtering concept is applied to the damping coefficient, which is shown in Fig. 4. The damping coefficient reflects the frequency sensitivity of the feeder loads. The estimated value for \( P_b \) is shown before and after applying a low pass filter in Fig. 5. The change in feeder power is obviously tracked by the estimator.

![Figure 4. Damping torque coefficient, LLSE output (\( D_d \)) and signal after filtering (\( \hat{D}_d \)).](image)

![Figure 5. Unknown power (\( P_b \)) before and after filtering.](image)

Recalling the assumption that the system angle will be unaffected by changes in load power, Fig. 6 shows the relative error of estimated stored energy when the number of machines or feeder stored energy to system stored energy ratio is increased. The error sharply increases when the feeder stored energy increases beyond 0.5% of system stored energy, due to the fact that by increasing the feeder inertia, the small-mass and infinite bus assumption will no longer be valid and the border bus angle variation is governed by the overall inertia in the feeder and system instead of the reactance of the flow path, see (5).

![Figure 6. Relative error occurs when load inertia becomes large.](image)
recorders will be activated based on monitored power. It should be noted that the procedure in Section II can be applied to any feeder in the system that has a weak connection to the system with a low contribution to system total stored energy. Although the contribution of a single feeder may be small, the total stored energy in specified feeders may be noticeable. It is not practical to apply the estimation procedure to all load feeders in a power system as the recording devices and communication requirements are not in place everywhere. It is more practical to select those feeders where, from preliminary observations, more rotating masses are available (e.g. large industrial feeders). The contribution of these feeders could be scaled up in order to detect the inertia for the proposed small-mass estimator. Moreover, if the step changes are very small, the sampling rate has to be sufficient to achieve reasonable estimation. Load ramping, when the ramping time is long generates an error in estimation as well. This is because the oscillation in active power is superimposed on a regular decrease in load which is then challenging for the linear estimator to account for. It also worth mentioning here that, in order to detect the inertia for the proposed small-mass oscillation against infinite bus, the theoretical sampling frequency should be at least $2f_{osc}$ referring to (8), which in our test case is around 7 Hz (i.e. sampling period 0.14 s). However, the practical sampling time for a good estimate is as low as 0.06 s in Fig. 7.

IV. SYSTEM INERTIA APPLICATION

The procedure described in Section II can be applied to any feeder in the system that has a weak connection to the system with a low contribution to system total stored energy. Although the contribution of a single feeder may be small, the total stored energy in specified feeders may be noticeable. It is not practical to apply the estimation procedure to all load feeders in a power system as the recording devices and communication requirements are not in place everywhere. It is more practical to select those feeders where, from preliminary observations, more rotating masses are available (e.g. large industrial feeders). The contribution of these feeders could be scaled up in order to represent the total contribution of all load feeders. The total stored energy in synchronous generator masses, which are usually known, are added to the estimated contribution from selected feeders which results in the total system stored energy available. It should be noted that the procedure in Section II is straightforward enough to be applied on each selected feeder independently as the triggering signals for recorders will be activated based on monitored power.

As discussed in Section III, to obtain a reasonable estimation, the change in feeder power and sampling rates should be sufficiently high. Usually, the monitoring devices in control centres do not offer such resolution. It is required to introduce recording devices in substations to perform the recording based on triggering criteria. The changes in feeder power can be used as the triggering criterion. The system requirements are the feeder recording capability and the communication capacity available at desired substations. Fig. 8 shows two possible configurations to record, send and analyze data. In Fig. 8(a) after triggering the recorder, data at a high sampling rate will be recorded. The substation then sends a ‘recorded signal available’ message to the centre to announce that data is ready. Upon receiving an acknowledgement from the centre, data will be sent to the centre where all analysis will be performed. This system requires more communication capacity and additional delays. However, if a processing device is available in the substation all analysis can be performed in the substation itself. If the inertia estimation was successful, the estimated stored energy available signal will be sent to the centre and upon acknowledgement the single stored energy value is sent, Fig. 8(b). This design requires lower communication but a large amount of processing in the substation. The control centre process in Fig. 8, when a new stored energy available signal is received, will check the consistency of the new estimate based on previous stored measurements and if successful, will update the stored energy of the corresponding feeder. Consequently, the daily, weekly and seasonal variation in feeders and system inertia can be observed and recorded. Two types of estimated stored energy can be defined based on this concept:

- Simultaneous system stored energy (SSSE)
- Non-simultaneous system stored energy (NSSE)

SSSE is the system total stored energy when all sources of inertia in the system are known at a specific time. This estimate is available after large signal disturbances, such as generator outages.
The feeder-based stored energy estimation proposed in Section II is of this latter kind. As load changes in the feeders will not happen simultaneously, their contribution to stored energy is assumed to be constant between consecutive measurements. Depending on the nature of the feeder loads, the update rates could be several times per day which is adequate to update the system stored energy.

V. CONCLUSION

High wind penetration in power systems, when the stored energy is particularly low, affects frequency stability. The current trend of increasing wind generation in those systems implies that the stored energy and available inertial sources in the system needs to be re-examined. Detailed knowledge of system inertia in real-time is needed by system operators to ensure adequate frequency stability margins. In this paper, the basis of a simple real-time system stored energy estimator is presented. The estimation method focuses on the unknown sources of inertia from selected feeders where recorded data of power and frequency is available. These feeders can be load feeders, small generating units or even wind farms. Small load changes in a feeder are used as a basis for estimation, which is based on the small-mass and infinite bus oscillation concept. The capability of the proposed method is shown using a test system. Errors in the estimation process and assumptions required for reasonable stored energy estimation, as well as system application principles, are discussed.

System inertia will not limit the operation of large power systems with a generating fleet composed of thermal power plants. However, it will be a concern for systems having low inertia with a goal of high wind penetration levels. Real-time stored energy estimation will be required in future for such systems. Sections III and IV show that communication stored energy estimation will be required in future for such plants. However, it will be a concern for systems having low inertia and limited communication.

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