A near-real time loss allocation methodology based on the power system states

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Abstract: Power losses in transmission systems are most of the time seen as a small amount (2-5%) from the total power carried over the network. However, transmission loss allocation may play a crucial role in the congestion management of balancing markets. Several loss allocation and loss cost allocation methods have been proposed and implemented in different markets. Most of these methods are intended to be used post market. This paper presents a novel near real-time loss allocation method suitable to be applied in real-time markets as envisioned in the smart grid context. The proposed method allocates the total system losses fairly to all the demand and generator buses, by taking into account the dynamical changes of the power network states, which are provided by an accurate state estimation. The power flows required to determine the allocated losses are executed after an economic dispatch procedure that ignores losses, making the choice of the slack bus an independent factor. The proposed method can be used as an accurate real-time pricing for network usage while the resolving of transmission congestion can be more reliable.

1. Introduction

1.1 Background

A considerable amount of energy is dissipated by the transmission and distribution power network while carrying the energy from the sources to the end users. Losses in power systems are generally seen to have two major components: the physical or technical losses that are the focus of this paper, and non-technical losses such as in-house consumption (hidden losses), energy theft, and metering errors. The latter are out of the scope of this work, even though for some countries they may represent a significant portion (sometimes over 50%) of the total power losses. From the financial point of view, the network losses are translated into an amount of money that cannot directly be linked to the amount of served power. There is also a long debate among stakeholders on who should actually pay for the losses and accordingly, one may distinguish between two schools of thought: the “beneficiary pays” and the “socialization” concept [1]. Within the European electricity markets, for example, one may see a wide range of approaches from definition of network losses to procurement, financial recovery and incentive schemes to reduce them [2].

Another aspect that plays an important role in the allocation of transmission losses is related to the electricity market design. Thus, one may distinguish between post market loss allocation and “in market” loss allocation methods. Post market loss allocation is the case when the electricity market closes, explicitly ignoring the transmission losses and the transmission congestion constraints (e.g., the case of the European electricity markets). “In market” loss allocation is the case where the transmission losses and their respective allocation are directly included in the market clearing algorithm (e.g., markets based on the “Locational Marginal Price” (LMP)). It is important to mention that there is an explicit decoupling of the three components in the markets that adopt LMP: energy, congestion, and loss costs [3]. Within this classification, loss allocation methods are mainly performed post market [4-9]. It should be noted that the procedure for allocating the losses, in an agreed or fair way, to each bus in the system is not a trivial task. Transmission losses depend on several variables that change continuously. Furthermore, the impact on system losses due to the change in supply or demand at any given bus might be different if it is averaged or if it is at its marginal edge. Thus, one needs to be careful when applying different approaches, in order to avoid false adjustments (for example, when resolving transmission congestion [10]).

1.2. Related works

A first classification within the post-market allocation methods distinguishes between four major implementations: (1) pro rata (PR); (2) marginal allocation; (3) unsubsidized marginal allocation; and (4) proportional sharing [11]. The last three implementations are based on power flow tracing algorithms. In practice one may see a combination of these four methods (e.g., PJM in the US uses marginal losses with pro-rata allocation).

A method where the losses of a network are allocated according to a mathematical relationship between the power at each end node and the DC power flow of the corresponding line is proposed in [12]. Allocation of losses, as well as congestion management based on DC power flow solutions, are common practical approaches of Independent System Operators [13]. However, it was shown that this approach can also lead to solutions of the locational marginal price that underestimate the cost of energy at the load

location in the case of congestion [14]. In such situations, AC power flow based solutions are needed and accurate loss allocation procedures are desirable to reduce this financial risk. Transmission loss allocation method using an AC power flow tracing method was adopted in [4] and [9]. The tracing algorithm uses the power flow results combined with the proportional sharing principle, in order to determine the contributions of loads and generators to power flow and the corresponding losses in transmission lines. However, the solution of loss allocation based on power flow tracing algorithms is dependent on the choice of the slack bus.

A consumption-based methodology of transmission loss allocation in deregulated power systems under open access is presented in [5]. This methodology calculates the portion of active power transmission losses caused by generators and the portion caused by loads using their contractual obligations. Within the open market framework all users share the network at the same portion of time (even though at some moments they do not inject or withdraw power) and their contribution to the transmission losses is hard to be separated. In [15] the Aumann-Shapley theory is used to identify the fairest way to divide the nonlinear and non-separable portion of active and reactive power losses on transmission branches between generation agents. In [7], the same authors approach the loss allocation problem as a game theory problem, using the Aumann-Shapley in parallel with circuit theory to allocate active and reactive power losses simultaneously to generators and loads. On the same approach in [16] it was shown that the allocation of losses following the Shapley Value Principle in conjunction with game theory approaches cannot lead to an optimal solution, however a Shapley value always exists. A point of criticism is that all these methods do not take into account the negative losses due to counter power flow, or they limit their study to the active power losses ignoring the impact of reactive power on the allocation of active power losses.

Incremental methods and loss allocation by integration can also be found in the literature [8], [17]. One of the most important issues of this topic is to reduce the difference between the sum of theoretically

allocated losses and the actual system losses (allocation error). Cheung et al. tried to reduce this error by integrating Newton's penalty factor [8]. However, they did not sufficiently reduce the allocation error due to the fact that they neglected the reactive power. The reactive power has been taken into consideration in [17], with the losses being allocated after integrating the partial differential of the system losses along a path that reflects the transaction strategy. It is though necessary for this method, that the bilateral transactions are known *a priori*.

1.3. Motivation and summary of contributions

Even though the power loss allocation might deal with small amounts of power compared to the bilateral transactions for example, they may be significant enough to create disputes among players sharing the same network even in a mature power market [18]. Then, a question that might arise is: would it be better to allocate these power losses in "real-time" or "near-real time"? The assumption is based on the same principle of the necessity of existence for the real-time market that corrects imbalances from the day-ahead market, including the actual physical transmission losses. Actors are already accustomed with the two forms of markets and their involved risk exposures. Therefore, a calculation of cost allocation for the transmission losses caused by each bilateral or pool based transaction might sound reasonable to approach. The loss allocation procedures described in this introductory section, by not being performed in real-time, are deprived of considerable advantages. Real-time loss allocation goes hand in hand with the adoption of smart grids and real-time billing of electricity. In this framework, a loss allocation procedure, accurate and near real-time is needed. The benefits of a real-time and accurate loss allocation procedure also expand to overcome financial risks encountered by Transmission System Operators that collect transmission congestion rights [13]. Moreover, it is shown that counting the impact on system losses due to the change in injection at any given bus plays an important role in setting transmission congestion issues. Since congestion incidents can occur at any time, loss allocation in frequent intervals can be vital for resolving them.

The loss allocation technique proposed in this work expands a previous work of the authors [19]. It was previously shown that taking into account the dynamical changes of the states of the power network leads to a better estimate of the actual power losses in the system. This paper expands the idea into a more accurate loss allocation technique, as well as a general formulation. This method can be applied to both LMP based markets, such as in the USA, as well as to financial balancing mechanisms for loss compensation, such as in Europe. More specifically, all the changes at the system buses are being tracked by a state estimator and are used to calculate the injected/withdrawn current to/from a load/generator bus. Taking into account the flow of current that causes the active power losses in a power system we actually count for the cross effect of active and reactive power flow on the active power loss calculation. When the next state estimator results are available, the difference in the system losses is allocated to all system buses according to how the difference in the current injected/withdrawn to/from each bus affects the current value of system losses. Thus, the losses are distributed in a more reasonable way to the demand buses and the generator buses of a power system. Note however, that the proposed method does not take into account the special case of generating buses operating in no-load mode or the presence of shunt branches in different locations where there might appear some “unfairness” in allocating transmission losses to all generating and load buses, as indicated in [20]. The contributions of this work can be summarized as follows: (1) the proposed method takes into account both active and reactive power flow components when calculating the allocation of transmission power losses; (2) it takes into account the negative losses due to counter power flow; (3) the proposed method overcomes the disadvantages of both AC power flow tracing methods and incremental methods for loss allocation by being free of the choice of the slack bus by calling an economic dispatch algorithm prior to the power flow call; and (4) it is experimentally shown that, by taking into account both active and reactive power component of the power flow, the allocation error is nearly zero (the difference between the theoretical and the actual allocation of the losses).

2. Preliminary notions

2.1 Definition

“Near-real time” refers to the time between two consecutive runs of a state estimator which are dependent on the time of measurement data collection. The state estimator can be executed between 1-5 minutes and in this work it is assumed that the estimated states are updated every 2 minutes. The assumption here is that the loss allocation procedure runs within this time frame, an assumption proved to be correct from our experimental cases.

2.2 Problem statement

We define the allocation of power transmission losses to generators and demands as the problem of tracing the contribution of each generator and demand to the total (aggregated) transmission losses within a time instance (between two consecutive steady conditions of the system). Thus, our approach is to use the actual measurements and a state estimator in helping to achieve this goal. Furthermore, in order to be free of the slack bus choice in the case of power flow run within the state estimator and the loss allocation procedure, an economic dispatch solution is used to indicate the targeted power output of each generator.

2.3 Theory behind the methodology

Active power losses in a power system depend on the change in supply or demand at any given network location, and more specifically on the current flow withdrawn from or injected to a bus. In [20] the authors propose the use of current injections/withdrawals at each bus to trace the transmission power losses. In the following, we propose to calculate in real time the losses and their respective allocation to each bus dynamically based on how the changes of the power network states (injected/withdrawn complex currents) at each bus affect the complex power transmission losses. It is important to take into consideration the direction of the current since, as it will be shown later, there are some cases where negative loss allocations arise due to counter-flows (the power flows that oppose the initial flows in a particular transmission line). This negative loss allocation is fair enough since the net effects of several

transactions simultaneously reduce the net active system loss. Thus, we consider that the power system losses are expressed as a function of complex current injections [21],

$$P_L = \sum_{i=1}^n \sum_{j=1}^n I_i R_{ij} I_j^* \quad (1)$$

where

n is the number of buses in the system

I_i is the current injected at bus i

R_{ij} is the real part of the Z_{bus} matrix at position i,j

The injected current at bus i can be expressed as,

$$I_i = |I_i| \cos \delta_i + j |I_i| \sin \delta_i \quad (2)$$

Substituting (2) to (1) the power losses can be calculated as,

$$P_L = \sum_{i=1}^n \sum_{j=1}^n |I_i| |I_j| R_{ij} \cos(\delta_i - \delta_j) \quad (3)$$

It should be noted that both long line (or “pi” model) and short line models are present in the test systems we detail in Section 4.

3. Proposed real time loss allocation method

It is important to mention what are the desirable features for a loss allocation method to be accepted by all parties sharing the network. These characteristics were first summarized in [11], [22], and for convenience are repeated in Table 1, where the near real time feature is further added. Table 1 presents a short comparison of the allocation methods surveyed in our work with respect to their characteristics. It should be noted that (✓) means that the method has the respective characteristic, (✗) that the method does

not satisfy the respective, and (–) that it is not mentioned in the respective reference whether the method has or has not the respective characteristic.

Table 1 Comparison of loss allocation methods based on their main characteristics

Method	Characteristic						
	<i>Reflects the magnitude of the power injection/ subtraction at/from each bus in the network</i>	<i>Considers the relative position of a bus in the network</i>	<i>Provides incentives/disincentives for generators and loads with respect to their relative location</i>	<i>Be consistent with the solved power flow, including reactive power losses</i>	<i>Simple to implement and understand</i>	<i>Considers counter-flows</i>	<i>Suitable for real-time applications</i>
<i>Pro-rata, consumption based [11]</i>	✓	×	×	×	✓	×	×
<i>Usage and Power-flow tracing [3], [4], [9], [11], [12]</i>	✓	✓	✓	✓	-	-	×
<i>Incremental based methods [8]</i>	✓	✓	×	×	✓	×	×
<i>Circuit Theory based methods[6], [7], [20]</i>	✓	✓	×	-	✓	-	✓
<i>Shapley value and game theory based methods [7], [15], [16], [22]</i>	✓	✓	✓	×	×	✓	×
<i>Proposed method</i>	✓	✓	✓	✓	✓	✓	✓

One may see our proposed method as a blend of network based power flow tracing method (eq. 2) and an incremental method approach (eq. 4.). Thus, following (2) and considering that the impedance matrix (Z_{bus}) of a system remains constant during the calculation process, then the active power losses can be expressed as a function of the magnitude and the angle of the injected/withdrawn current at each bus of the power system. It should be noted that as long as the calculation of the transmission power losses in the system is based on injected currents rather than injected power only, the calculations take into account

both the active and reactive power components of each bus. For convention, injected currents are considered to be negative values, while withdrawn currents are considered to be positive values. Thus, the total differential of the power losses is given by,

$$dP_L = \frac{\partial P_L}{\partial |I_1|} d|I_1| + \frac{\partial P_L}{\partial |I_2|} d|I_2| + \dots + \frac{\partial P_L}{\partial |I_n|} d|I_n| + \frac{\partial P_L}{\partial \delta_1} d\delta_1 + \frac{\partial P_L}{\partial \delta_2} d\delta_2 + \dots + \frac{\partial P_L}{\partial \delta_n} d\delta_n \quad (4)$$

Substituting (3) into (4) it follows that the total differential of the power losses for a system with n buses is,

$$dP_L = 2 \sum_{j=1}^n \sum_{i=1}^n |I_i| R_{ij} \cos(\delta_i - \delta_j) d|I_j| - 2 \sum_{j=1}^n \sum_{i=1}^n |I_i| |I_j| R_{ij} \sin(\delta_i - \delta_j) d\delta_i \quad (5)$$

If the variations of the current magnitude and angle, $d|I|$ and $d\delta$, are small enough, the differential of the power losses can be considered as the corresponding change of the power losses. The variations of the injected current magnitude and angle at each bus can be captured using a power system state estimator. It should be noted that the state estimator takes into account all the regulating devices as well as the phase shift of the transformers. In this sense, both voltage regulation devices and phase shift transformers are considered in the proposed method since the estimated states provided by the state estimator are used in the methodology.

The states of the power system (i.e., voltage magnitude and angle at each bus) are typically estimated in the time interval of 1 to 5 minutes. Thus, in steady state operation, the difference in the injected current at each bus can be considered small enough to calculate the total change of the active power loss in the system. By decomposing (5) in terms of $d|I|$ and $d\delta$ for each bus, the difference in total power system losses can be allocated to all the buses of the system according to the responsibility share of each bus, which can be calculated as,

$$dP_{Li} = 2 \sum_{j=1}^n |I_j| R_{ji} \cos(\delta_j - \delta_i) d|I_i| - 2 \sum_{j=1}^n |I_i| |I_j| R_{ij} \sin(\delta_i - \delta_j) d\delta_i \quad (6)$$

The types of measurements used in a contemporary state estimator are the real/reactive power injections and flows, and voltage magnitudes [23]. With the deployment of Phasor Measurement Units (PMUs) in the measurement layer of power systems, bus voltage phasor measurements and line current

phasor measurements are available. Due to the accuracy of the PMU measurements, their inclusion to the measurement vector of the contemporary state estimator improves the accuracy of the conventional state estimator considerably. Such a state estimation scheme that includes both conventional and PMU measurements is called hybrid [24]. Even though the proposed methodology can also be used when a conventional state estimator is available, the presence of PMU measurements (and thus a hybrid state estimator) improves the results considerably, as will be demonstrated in Section 3.

Table 2 Transmission power losses – proposed methodology

<p><u>Main allocation method:</u></p> <p>Initialization: $t=0$; Run Offline Scenario; End_Initialization;</p> <p>WHILE State Estimator (SE) is updated Get the states given by the State estimator (V, θ); Allocate all losses using (6);</p> <p>IF $\sum(Allocated\ losses) - Total\ Losses\ from\ SE > Threshold$ THEN Run Offline Scenario; END_IF END_WHILE</p>	<p><u>Offline Scenario (after initialization):</u></p> <p>Calculate P_i and Q_i (from the states given by the current updates of the State Estimator) Calculate P_{d_k} and Q_{d_k} (from the states given by the current updates of the State Estimator) Step=1; Economic Dispatch; Power Flow (and calculate $P_{d_k}^{offline}$); Allocate all losses to all non-zero injected buses equally;</p> <p>WHILE $P_{d_k}^{offline} - P_{d_k} > \varepsilon$</p> <p>Step=Step+1; $P_{d_k}^{offline} = 1.001 * P_{d_k}^{offline}$; Economic dispatch; Power Flow; Allocate the difference in total losses to the buses using (6); END_WHILE</p>
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Since the amount of the losses allocated to each bus is not known *a priori*, an offline scenario is executed for allocating the transmission losses at the initial stage. Before creating an offline scenario, it is first needed to calculate the demand of each load bus of the system (P_{d_k}, Q_{d_k}) at the present state (t). This can be achieved by calculating the active and reactive power injections at each bus (P_i, Q_i) using the results of the state estimator. When the demand of each load bus is known, the offline scenario can be created. At this point, the total load of the system is assumed to be equal to the sum of the minimum production of all the generators which are committed in the system, keeping however the ratio of the demand of each load bus to the total system load the same as at the present state (t). Thereafter, the demand of each load bus is increased by a small percentage until the values of the loads reach the ones of

the present state as it is presented in the pseudo-code of the offline scenario. The increase percentage has been chosen to be 0.1% to ensure that the change of the current magnitude and angle at each bus are small enough and thus the differential of the power losses can be considered as the corresponding change of the power losses. Moreover, it is secured that the values of the loads at the final step of the offline scenario, do not exceed the ones of the present state (e.g., $\varepsilon = 1 \times 10^{-3}$).

For the first step of the offline scenario, a power flow is executed and the total system losses are equally allocated to all generator and demand buses of the system. It should be noted that this initial allocation is negligible compared to the final allocation achieved in the real-time scenario since the transmission losses at this point are very small. Next, a power flow is executed at each step that the loads are increased and (6) is applied for allocating the losses at each bus. This procedure is performed until the loads reach their corresponding values of the present state. Furthermore, prior to each power flow execution in the offline scenario, the power output of each generator is determined by an economic dispatch. Thus, by knowing the loss allocation at time t , (6) can be used every time the states are updated by the state estimator in order to fairly allocate the change in the total transmission losses. Since the power flow execution is based on economic dispatch, the final loss allocation will not be dependent on the choice of the slack bus.

After the initial offline scenario, the algorithm continues with real-time executions. In the interval between two such real-time state estimator executions, the summation of the allocated losses is checked to be equal with the actual losses of the system. If the difference between them is larger than a predefined threshold, this means that the losses are not allocated reasonably. This difference may be due to the high variation of the current magnitude and current angle, resulting from the change of the operating condition at that point. In this case an offline scenario is used again, taking as initial values the loads of the system at the present time. The threshold can be chosen by the user, based on the accuracy required. The lower the threshold, the more often offline scenarios will need to be executed.

4. Case studies and discussion

The methodology proposed in this paper has been tested on IEEE test systems. In this paper, the results for the IEEE 9, 118 and 300-bus systems are shown. All test systems have been implemented in the PowerWorld software. For each system a daily load profile scenario has been created that captures load variations that can typically be encountered in power systems (e.g., steep load increase/decrease, smooth variations, peaks, and valleys). For the state estimation runs, it is assumed that PMU measurements are available. The PMUs were placed according to the methodology of [25], resulting to the placement of a relatively small number of PMUs (2, 22, and 44 PMUs in the 9, 118 and 300-bus system respectively). The systems are thus not fully observable by PMUs. The algorithm is executed every two minutes. This time interval is user-selected. It can follow the state estimation execution runs of the system under study, or the market requirements.

4.1 IEEE 9-bus system

For the IEEE 9-bus system the total load profile for a day is shown in Fig. 1(a), while Fig. 1(b) presents the corresponding variation of the demand in each load bus. The generation of each generator bus is shown in Fig. 1(c). The generation output of each generator is an approximated solution of an economic dispatch procedure with transmission losses. The transmission losses are initially approximated with a quadratic function using the B-loss coefficients. The model uses a quadratic approximation of the cost function of each generator and it runs a quadratic programming algorithm for finding the optimal solution. This initial solution is then further refined with the state estimator updates.

Since at $t=0$ the load at each demand bus is known, then the offline scenario is run in order to allocate the losses at the present state. This procedure finishes prior to the provision of the updated states by the state estimator, and then the online scenario starts.

In this case study, the initial loads at demand buses 5, 6, and 8 are set to 83.1 MW, 59.83 MW, and 66.48 MW respectively, while the minimum production for each generator is 10 MW (30 MW total).

Assuming that all the generators have been committed for generation (e.g., in a day ahead market or after the balancing market was cleared), the initial total load for the offline scenario is set to 30 MW.

More specifically, the load at bus 5 is set to 11.91 MW, the load at bus 6 is set to 8.57 MW and the load at bus 8 is set to 9.52 MW (30 MW total). These values have been chosen in order to have the same percentage difference as the demand buses had at the initial state of the real-time scenario. In this way, the demand at each load bus is increased with the same small percentage steps until each load bus reaches the corresponding demand of the real-time scenario at $t=0$.

At the initial step of the offline scenario the system transmission losses are equal to 0.1770 MW. These losses are equally distributed to each load and each generator bus of the system. Therefore, each generator and demand bus of the system is charged with 0.0295 MW. Having this initial loss allocation as a reference point, the loads are increased in small steps until they reach their value at the present state of the real-time scenario. At each step a power flow is performed and (6) is used in order to find the losses allocated to each bus until $t=0$. Since these losses are much higher than the initial allocated losses of the offline scenario, the 0.0295 MW each bus was charged with can be considered negligible and the allocated losses of the present state can be used as the reference point for the real-time scenario.

As updated states are provided by the state estimator, the share in the total losses for each bus is calculated using (6) and is added to the allocated losses of the reference point. The allocated losses of the new state become the new reference point for the next updated state and this procedure continues alongside with the state estimator updates, provided that no significant change happens in the system. If, however, a sharp demand change or a fault occurrence is observed, an offline scenario should be run again. In the case studies of this paper, a threshold of 5% for the allocation error has been selected.

Fig. 2 presents the resulting loss allocation of a real-time scenario according to the variation of the demand in each load bus of Fig. 1(b) and the generation of Fig. 1(c). The summation of the allocated losses at each point of time is very close to the actual losses of the system as shown in Fig. 3. Specifically,

the largest difference observed between the actual losses and the summated allocated losses in this scenario was 3%. Thus, an offline scenario is not necessary to be used.

Fig. 1. (a) Total load profile for a day; (b) Load profile of each demand bus for a day; (c) Generation at each generator bus.

Fig. 2. Real-time loss allocation for the IEEE 9-bus system. Buses 4, 7, and 9 are not presented since they are zero injection buses.

Fig. 3. Comparison between the actual system losses and the summation of the allocated losses at each point of time.

It is possible that the proposed near real-time loss allocation method can allocate negative losses to some buses (bus 1 and 8). In fact, Fig. 2 also shows that as the generation at bus 1 and the demand at bus 8 are increased, the corresponding negative losses, allocated to each bus, are decreased. This observation leads to the conclusion that the transmission losses increase/decrease, while the generation of bus 1 or/and the demand of bus 8 are decreased/increased respectively.

For explanation purposes, two scenarios have been created in order to examine the above conclusion. For the first scenario, in order to study how the system losses are affected when the contribution from bus 1 is reduced, the maximum operating point of the generator at bus 1 was limited to 45 MW (Fig. 4(a)). For the second scenario, in order to investigate the effect of the reduction of the demand at bus 8 on the system losses, the load profile of the specific bus was decreased to half the capacity compared to the initial case (Fig. 5(a)).

Indeed, Fig. 4(b) shows that when the generation at bus 1 is lower than the initial case (since now it is limited to 45 MW) the total transmission losses are higher. Fig. 5(b) also demonstrates that the transmission losses are higher when the demand at bus 8 is lower. These two extra scenarios indicate clearly the reason for bus 1 and bus 8 being compensated, since a potential decrease/increase at bus 1 generation or/and bus 8 demand, would cause an increase/decrease in the transmission losses respectively.

(a)

(b)

Fig. 4. (a) Generator productions when the maximum operating point of generator 1 is limited to 45 MW; (b) Transmission losses of the initial scenario compared to the transmission losses when generator 1 is limited to 45 MW.

(a)

(b)

Fig. 5. (a) Demand at buses 5, 6, and 8 with the load at bus 8 equal to one half compared to the initial scenario; (b) Transmission losses of the initial scenario versus transmission losses when the load at bus 8 is reduced by half.

4.2 IEEE 118-bus system

The 118-bus system has been used in order to investigate the behavior of the proposed methodology in large systems. Two new issues are examined in this case study: (a) the type of state estimator used and (b) the random variation of the system loads.

The state estimator is an important part in the proposed loss allocation methodology; a comparison between the use of a conventional and a hybrid state estimator is performed. The main difference in the two types of state estimator is the accuracy. More specifically, the hybrid state estimator is more accurate

than the conventional one due to the presence of PMU measurements in its measurement vector [20]. The effect of the accuracy of the state estimator on the proposed methodology is examined by determining the allocated losses using the estimated states provided by a conventional and a hybrid state estimator.

In order to achieve a more realistic scenario, the loads of the system have been set to vary randomly, in the sense that at each instant some loads increase whereas other loads decrease. Fig. 6 shows the daily load profile which has been used. The proposed real-time loss allocation method has been applied by using both conventional and hybrid state estimators with the system states being updated every two minutes.

Fig. 6. Profile of a daily total load for the IEEE 118 bus system.

In Fig. 7(a) the summation of the allocated losses is shown for a conventional state estimator and in Fig. 7(b) for the hybrid state estimator (note that the actual losses indicated by the solid line are the same in both figures). Comparing the allocated losses for the two types of state estimators it can be concluded that the difference between the actual losses and the allocated losses is large when a conventional state estimator is used. This is because the proposed methodology is very sensitive to large system variations which in the case of the conventional state estimator occur often due to the large variance in the estimation of the states (limited accuracy). On the contrary, the allocated losses based on a hybrid state estimator (Fig. 7(b)) are found to be more accurate, due to the small variance of the estimated states. Moreover, by setting a 5% acceptable difference between the actual total system loss and the summation of the allocated losses, it can be seen (Fig. 7(c)) that the results can be improved by running two intermediate offline scenarios.

Specifically, at the 580th minute of the simulation, it is observed, for the first time, a difference between the actual total system loss and the summation of the allocated losses that exceeds the acceptable threshold of 5% (allocation error). Another offline scenario at the 1080th minute needs to be run since the allocation error exceeds the threshold. In the end, with two offline scenarios we can achieve accurate losses allocation.

Fig. 7. (a) Summation of the allocated losses using a conventional state estimator; (b) Summation of the allocated losses using a hybrid state estimator; (c) Improved summation of the allocated losses using a hybrid state estimator and two intermediate offline scenarios.

The results of this case study show that if for any reason the difference between the total system losses and the summation of the distributed losses diverges from an acceptable threshold, the use of an offline scenario can restore this difference within desirable limits. The use of an offline scenario is feasible

as it can be run in a time framework shorter than the one needed by the state estimator to update the states. Specifically, for the IEEE 118-bus system, the total time needed to execute an offline scenario using MATLAB was 1.2 minutes, based on a computer with an i5-2400 processor, 3.10 GHz and 4 GB RAM.

4.3 IEEE 300-bus system

The proposed loss allocation methodology is also applied to the IEEE 300-bus system to demonstrate its effectiveness in such a large scale system. The daily load profile that is used in the IEEE 300-bus system is shown in Fig. 8a.

Fig. 8. (a) Profile of a daily total load for the IEEE 300-bus system; (b) Summation of the allocated losses using a hybrid state estimator

The estimated states from the hybrid state estimator were used in the proposed methodology for allocating the losses to all the non-zero injection buses. In summary, the methodology is successfully applied to the large scale system as demonstrated in Fig. 8b where the actual losses and the summation of the allocated losses is shown. This shows that the performance of the proposed methodology is very promising in a more practical situation.

5. Conclusions

This paper proposes a new real-time loss allocation method, where the total system losses are fairly distributed to all the demand and generator buses, by taking into account the dynamical changes of the power network states. This methodology, based on continuously updating the system states, ensures an accurate allocation of the system losses in near real-time and can be a suitable tool to be adopted in the energy management system of the power system.

This procedure can give the right signals to participants in the market and can capture both average loss changes, as well as marginal transmission loss changes. It can also play a significant role towards implementation of concepts, such as the real-time billing in the electricity market. Furthermore, real-time loss allocation can prove to be vital in avoiding false adjustments for resolving transmission congestion. The scheme proposed here is neither difficult nor adding excess computational burden; this implies that this methodology can be easily implemented in the control centers of power systems.

5. References

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