

Impact of Overexcitation Limiters on the Power System Stability Margin Under Stressed Conditions

Georgios Anagnostou, *Student Member, IEEE*, and Bikash C. Pal, *Fellow, IEEE*

Abstract—This paper investigates the impact of the overexcitation limiters (OELs) on the stability margin of a power system which is operating under stressed conditions. Several OEL modeling approaches are presented and the effect of their action has been examined in model power systems. It is realized that, more often than not, OEL operating status goes undetected by existing dynamic security assessment tools commonly used in the industry. It is found that the identification and accurate representation of OELs lead to significantly different transient stability margins. Unscented Kalman filtering is used to detect the OEL activation events. In the context of stressed system operation, such quantitative assessment is very useful for system control. This understanding is further reinforced through detailed studies in two model power systems.

Index Terms—Kalman filters, power system dynamics, power system security, stability criteria.

NOMENCLATURE

δ	Rotor angle.
$\hat{z}$	Column vector of predicted measurements.
$\lambda_{\max}$	Innovation ratio ceiling value.
λ	Innovation ratio.
ω, ω_b	Rotor speed and its base value.
σ_ω	Standard deviation of process noise.
σ_v	Standard deviation of measurement noise.
θ	Stator voltage phase.
a	Exponent corresponding to the slope dP_L/dV at $V = V_0$.
b	Exponent corresponding to the slope dQ_L/dV at $V = V_0$.
D	Rotor damping constant.
E'_d	Transient emf due to flux in q-axis damper coil.
E'_q	Transient emf due to field flux linkages.
E_{fd}	Generator field excitation voltage.

f	Column vector of system differential equations.
F_{HP}	Fraction of total turbine power generated by High Pressure section.
g	Column vector of system algebraic equations.
H	Generator inertia constant.
I	Stator current magnitude.
i	i th generation unit or i th bus.
I_d, I_q	d -axis and q -axis components of the stator current, respectively.
I_{fdlim}	Generator field current limit.
I_{fd}	Generator field current.
k	k th time step.
K_1	OEL timer non-windup lower limit.
K_2	OEL timer non-windup upper limit.
K_A	Static voltage regulator gain.
K_r	Summed Type OEL's non-operation coefficient.
L_{ref}	Governor load reference.
M, N	Number of generation units and buses, respectively.
P_L	Active power demand.
P_z	Covariance of predicted measurements.
Q_L	Reactive power demand.
R_s	Armature resistance.
R_{gov}	Permanent droop.
S_1	Ramp-up/Ramp-down coefficient.
T	Matrix transpose.
t, T_0	System time and system sampling period, respectively.
T'_{d0}	d -axis transient time constant.
T'_{q0}	q -axis transient time constant.
T_G	Governor time constant.
T_m, T_e	Mechanical and electrical torque inputs, respectively.
T_x	OEL Integral Control time constant.
T_{CH}	Time constant of main inlet volumes and steam chest.
T_E	Generator's exciter time constant.
T_{RH}	Time constant of reheater.
V	Column vector of bus voltages.
V_{OEL}	OEL output.
x	Column vector of system state variables.

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The authors are with the Department of Electrical and Electronic Engineering, Imperial College London, London, SW7 2AZ, U.K. (e-mail: georgios.anagnostou11@imperial.ac.uk; b.pal@imperial.ac.uk).

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X'_d	d -axis transient reactance.
X'_q	q -axis transient reactance.
x_1, x_t	OEL timer input and output, respectively.
x_2	Input to OEL of summed type control functions.
X_d	d -axis synchronous reactance.
X_q	q -axis synchronous reactance.
x_{gov}	Governor output.
x_{rh}	Turbine steam flow in the reheater.
x_{tb}	Turbine inlet steam chest.
y	Column vector of bus voltages.
z	Column vector of measurements.

I. INTRODUCTION

ELECTRIC power networks all over the world are experiencing significant operational challenges [1]. Primarily shift towards the renewable energy based new generation technologies coupled with increasing demand and lack of investment in transmission level have pushed the system to operate close to its limits [2]. Such operating situation at times stresses the system. When a stressed system experiences contingencies, it is likely to face partial to complete supply shutdown. In the context of network operation and control, it is very necessary to assess the security margin. Such margin is obtained through static security analysis. Typically static state estimation results are used as inputs. However, a power system, especially under a stressed situation, operates with some devices reaching operational limits which are not accurately characterized in the static model. This was further confirmed by the 1996 North American Power Blackouts in WECC system where the planning model did not include the accurate model of limiting devices such as overexcitation limiters (OELs) [3]. Various contingency analyses and stability assessments of the planning model were thus based on inaccurate initial operating conditions giving rise to different conclusions [4]. Dynamic security assessment (DSA) [5], [6] is a more useful approach. Also, in DSA, accurate representation of OELs has a significant effect on the quantitative results [4]. It assumes that the power system operates at normal steady state as against quasi steady state. Recent implementations of DSA tools stressed the importance of capturing the actual system condition and operating status of the devices [7].

The inclusion of correct initial conditions in stressed power system operation has a significant influence on the computed value of the stability margin. There is no concrete definition of a 'stressed system' let alone the methods of accurately representing it [8]. There is no easy way to identify the stressed situation which itself in its own deserves research attention. In this paper, since the assessment of the OELs operating status's impact on the stability margin is of primary focus, the operation of synchronous generator under the activation of OEL is taken as a stressed operating condition for the generator. There have been research efforts [9], [10] in investigating the system dynamics when synchronous generators operate with their overexcitation limit reached. But the effort concentrated

primarily on the manual control. The approaches analyzed do not suit modern and fast excitation control systems [11]. There have been various models [11]–[15] of OELs but they mainly target at study and analysis of long-term voltage stability problems. For angle stability studies, it is very important to include the OEL dynamics and limits to obtain correct angle stability margin under stressed conditions [4], [11]. Faults close to generator buses activating OELs that bypass AVRs potentially trigger transient instability [16]. Highly sophisticated OEL designs enable these devices to self-modify their limits and internal settings depending on conditions related to factors such as rotor hydrogen cooling pressure and temperature [11], [17]. Therefore, the inclusion of OEL dynamics in detail for stability assessment remains an important research challenge. In this context, this research effort leads to the following contributions:

- to examine the way the overexcitation limiter activation following a contingency affects the power system transient stability limits;
- to investigate how different OEL models influence the angle stability margin;
- to propose a stressed system condition indicator.

The remainder of this paper is organized as follows: In Section II, the power system modeling considerations are presented and, in this context, the OEL operation principles are analyzed, as well as its modeling options used here are stated. Section III includes the case studies evaluating the effects of different OEL models on the transient stability margin, in two model power systems; the 9-bus, 3-machine system used in [18] and the IEEE benchmark 68-bus, 16-machine system, representing the inter-connected New England (NETS) and New York (NYPS) power systems, which are connected to other 3 geographical regions [19]. Section IV presents a way to identify stressed system conditions, from the viewpoint of OEL activation. Section V concludes the paper.

II. POWER SYSTEM MODELING

A. Synchronous Generators

It is well known that in transient stability studies a power system can be represented by the following general set of equations, combining the components describing differential equations and the network corresponding algebraic equations [20]:

$$\begin{aligned}\dot{x} &= f(x, y) \\ 0 &= g(x, y).\end{aligned}\tag{1}$$

In the above equations, x represents all system state variables and y is a vector of all bus voltages.

Synchronous generators constitute the core of a power system. Depending on the level of the study detail, various models have been reported in the literature. A concise presentation of synchronous generators models can be found in [18] and [21]. In the context of this paper, the transient [22] and the subtransient two-axis models [19] have been used for two test system models.

B. Overexcitation Limiters

The basis of the OEL operation arises from the generator field winding's thermal capability [15], [23], as shown in Fig. 1. Any-

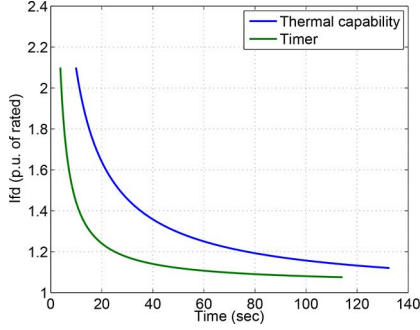


Fig. 1. Rotor thermal capability curve and OEL Timer curve [15].

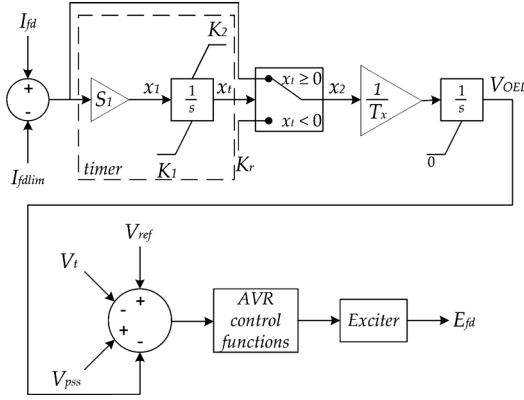


Fig. 2. Summed type overexcitation limiter [24].

time the field current value exceeds the acceptable levels, the OEL has to act in order to keep the field current within the appropriate range. OEL's activation is dictated by a timer, which compares the field current value to a minimum limit value, in accordance with the generator's rotor capability curve. As soon as the timer block output becomes positive, the signal is passed through the OEL block output and it is compared with the AVR's output signal. OELs are distinguished into two categories [12], [13]:

1) *Summed Type OELs*: In this case, the OEL output is added as a signal in the summing junction of the synchronous generator's AVR [13]. Here, the timer is represented by an integrator. This OEL type as well as the way it is connected to the AVR are illustrated in Fig. 2. In our case, the summed type OEL model includes integral control of field current and the equations characterizing its operation are the following ones [24]:

$$x_1 = S_1(I_{fd} - I_{fdlim}) \quad (2)$$

$$\dot{x}_t = \begin{cases} 0 & \text{if } (x_t = K_2 \text{ and } \dot{x}_t \geq 0) \\ & \text{or } (x_t = K_1 \text{ and } \dot{x}_t < 0) \\ x_1 & \text{otherwise} \end{cases} \quad (3)$$

$$x_2 = \begin{cases} I_{fd} - I_{fdlim} & \text{if } x_t \geq 0 \\ K_r & \text{if } x_t < 0 \end{cases} \quad (4)$$

$$\dot{V}_{OEL} = \begin{cases} \frac{1}{T_x} x_2 & \text{if } x_2 > 0 \\ 0 & \text{if } (x_2 \leq 0 \text{ and } V_{OEL} = 0). \end{cases} \quad (5)$$

K_1 is chosen in a way for the OEL to act within field winding's thermal capability [24], as shown in Fig. 1.

2) *Takeover Type OELs*: Here, the OEL bypasses the AVR, following its activation [13]. It has also been noted as OEL of

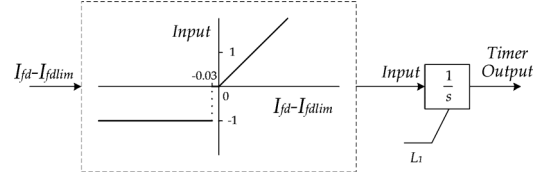


Fig. 3. Timer of a takeover type overexcitation limiter.

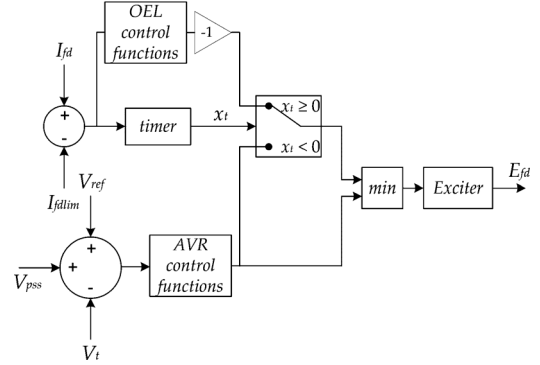


Fig. 4. Takeover type overexcitation limiter under control signal substitution scheme [13].

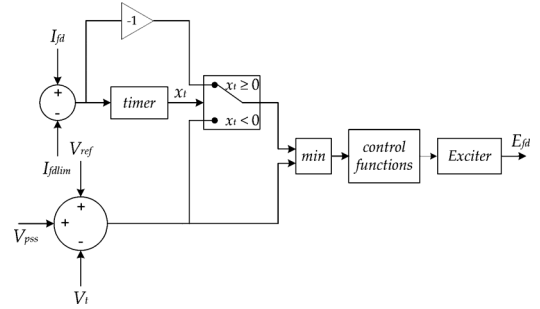


Fig. 5. Takeover type overexcitation limiter under error signal substitution scheme.

“hard” or “auctioneering” type [12]. The timer is represented by an integrator whose input depends on the difference $I_{fd} - I_{fdlim}$. If it is negative and lower than -0.03 p.u. (corresponding to normal operating conditions), the input is a negative number, whereas a positive difference results in a positive input, which depends on the difference itself. This particular case represents the inverse time characteristic, whereas, if a positive difference would be associated with a positive constant number as the timer block, this case would reflect the fixed time OEL [12], [15], [25]. If the difference lies within the range $[-0.03, 0]$ then the input is zero; this represents the hysteresis [15], thus the OEL is activated when the difference $I_{fd} - I_{fdlim}$ is greater than the upper limit of this interval, but it will stop limiting the field voltage as soon as this difference becomes lower than the lower limit of the interval, in order for limit cycling to be prevented. The logic on which the timer is based is shown in Fig. 3.

Two design schemes have been reported in the literature, which depends on the values of OEL's control blocks: The control signal substitution (CSS) scheme and the error signal substitution (ESS) scheme, depicted in Figs. 4 and 5, respectively. In both figures, the minimum gate ensures both the OEL signal passing to the exciter in stressed conditions, and

the return to voltage control when less excitation is needed, dictated by the operating conditions. The equations describing both schemes are based on the same logic, but the ESS scheme is the case when the OEL and the AVR have identical control blocks [13]. The OEL (of any of the two schemes) should be initialized according to the following equations [13]:

$$\dot{x}_t = \begin{cases} -1 & \text{if } I_{fd} - I_{fdlim} < -0.03 \\ 0 & \text{if } -0.03 \leq I_{fd} - I_{fdlim} \leq 0 \\ I_{fd} - I_{fdlim} & \text{if } I_{fd} - I_{fdlim} > 0 \end{cases} \quad (6)$$

$$E_{fd} = E_{fd0} + \Delta E_{fd} \quad (7)$$

$$T_E \Delta \dot{E}_{fd} = -\Delta E_{fd} - V_{OEL} \quad (8)$$

$$V_{OEL} = \frac{1}{sT_x} (I_{fd} - I_{fdlim}) \quad (9)$$

and $\Delta E_{fd} = 0$ at the time of switching. It has to be noted that (6) corresponds to the timer operation, whereas (9) represents the CSS case, where integral control of the field current has been considered. For the ESS case, the quantity $1/sT_x$ is replaced by the control of the corresponding AVR used, which in this case is K_A (Simple Static AVR).

C. Automatic Voltage Regulators

Selecting the appropriate model for the automatic voltage regulator (AVR) is an important part of system model building, since it has to be compatible with the OEL type it is associated with [12]. Here, the AVR of DC1A type has been used when the OEL is of summed type [18], whereas for the cases according to which OELs of takeover type have been applied, simple static voltage regulators have been utilized [24].

D. Loads

In the context of this analysis, loads are primarily modeled as of constant impedance type, but in several cases composite load models have also been considered. Among various ways of nonlinear load modeling, here the exponential model has been preferred, without any frequency dependency of load characteristics [20]:

$$\begin{aligned} P_L &= P_{L0} \left(\frac{V}{V_0} \right)^a \\ Q_L &= Q_{L0} \left(\frac{V}{V_0} \right)^b. \end{aligned} \quad (10)$$

In the above equation, the values of V_0 , P_{L0} and Q_{L0} correspond to the initial conditions.

III. STABILITY LIMITS CALCULATION

A. Methodology

All power system components in both test systems were modeled according to the earlier description. In order for the stability limits to be calculated, an iterative procedure has been established, whose main parts are the following ones:

1) *Initialization*: Initial conditions for the dynamic variables are generally obtained from power flow and solving $\dot{x} = 0$, thus $f(x, y) = 0$. However, when an OEL is in operation as apprehended in stressed cases the dynamics evolve ($\dot{x} \neq 0$)

and merely solving $f(x, y) = 0$ will result in incorrect initial system state. Thus, the initialization of the system cannot be done in this way when an OEL has been activated. Since the practice in contingency studies is to simulate the faulted and the post-fault system for calculation speed purposes [27], [28], in order to follow this practice, and at the same time consider the OEL operation at the start of the simulation (corresponding to the faulted period), the assumed initial value regarding the OEL's timer is zero, considering that the event happens at the time that the OEL is about to operate, and the initial field current value is 1.06 p.u. Therefore, OEL operation during the transient period is reassured and, at the same time, the equation $f(x, y) = 0$ is respected, since the system operates as normal, until the OEL dynamics replace the AVR dynamics. The computation of stability margin with such initialization will correctly capture the impact of OEL operation.

2) *Power System Simulation*: The fault is applied at $t = 0$ and is cleared at a specified clearing time, leading to the post-fault system simulation. Each contingency is based on the rationale, according to which a fault is applied to a bus close to a generator, and the fault clearing is coupled with line tripping [27], [28]. It has to be highlighted that the only faults examined are those close to generator buses, since these are the cases of rotor angle stability interest, in contrast with cases where faults are close to loads, which are examined from the voltage stability point of view [29]. The maximum simulation time is 10 s, since the focus is on the transient period, and longer simulations would require the modeling of additional devices, such as on-load tap changers (OLTCs).

3) *Stability Assessment*: Power system transient stability margin is usually based on critical clearing time (CCT) or power limits (PLs) calculation [27]. The CCT is associated with the minimum time that a fault has to be cleared in order for the system to be stable, whereas the PLs refer to the maximum amount of total generation and load levels enough to ensure system stability, for a predetermined fault clearing time (CT) value. However, the variety of generation and load allocation solutions arising from PLs calculation make the use of CCTs more convenient as stability limit indicators [27]. The CCT calculation is based on an iterative heuristic method (binary search) [27], according to which, starting from an initial CT value, which is high enough in order for the system to be unstable, successive simulations are carried out, until the difference between the CT of an unstable simulation and the CT of a stable one to be lower than a specified tolerance, which in this case is 15 ms. The maximum difference between the rotor angles of any two system machines serves as the instability index. According to this, a system is denoted as unstable if the difference between the rotor angles of any two machines reach a predefined limit within the simulation period, otherwise it is stable. For this purpose, several values have been used in literature [30]. In our cases, the maximum angular deviation is set to 180° . A similar procedure is followed in order for the power limits to be calculated, according to which, for a specified CT value, starting from initial power level values, the stability conditions are assessed as previously stated and, depending on whether the system is stable or not, the power levels are increased or lowered, respectively. Similarly to the

CCT calculation, the binary search method is used until the difference between the power levels of an unstable simulation and the ones of a stable one to be lower than a specified tolerance, which in this case is approximately 2% of the total system capacity. It has to be noted that there are various policies regarding generation and load reallocation, and each one affects the system stability status in a different way [27]. In this paper, in every iteration the system levels are initialized in a way that the active power of each machine is increased or decreased proportionally to its previous power level and the same scheme applies to loads' active and reactive power, in order not to change their power factors.

B. Test System 1: 9-Bus, 3-Machine System

The previous methodology was applied to a 9-bus, 3-machine system model, which can be found in [18]. The transient stability limits of this system were calculated for a set of contingencies as listed in [27]. The CCT values were calculated for the case when all machines operate under normal operating conditions (i.e., without any OEL operation during the transient period) as well as the case when the OEL of the generator in bus 1 operates during the transient period. It has to be noted that this is the only machine whose OEL has been considered to operate in the stressed operation case. This is based on the logic according to which the only generators to be considered as prone to limitation by OELs are the ones operating in overexcitation mode, having a power factor less than 0.95. In addition, the CCT values for all contingencies had to be recalculated for normal conditions when an OEL of takeover type operated, since in this case a static voltage regulator was used, whereas for cases when summed type limiters were used, AVR of DC1A type were used. The system initialization was performed as specified in [18], whereas the initialization data regarding the OELs are listed in Appendix B.

The results are shown in Table I for the summed type OEL application (Case Study 1A), and in Table II for the takeover OEL application (Case Study 1B), considering both CSS and ESS schemes. It can be clearly noticed that the summed type OEL has no impact on the stability margin. This is something which could be expected, since it has been characterized as “soft” in the literature [12], [31], because the limit imposed is influenced by the other inputs to the voltage regulators as well. On the other hand, the takeover OEL's influence on system stability margin is significant in some cases, making it considerably lower. As far as OELs of takeover type are concerned, the CCT variations are ‘translated’ into PL variations, in order to show in another way how the stability margin is influenced. The PL variations were calculated under the assumption of system normal operation, but for every contingency the CT is kept constant and its values are the CCTs for the stressed cases. Therefore, under normal conditions, the system power levels are increased until the system becomes unstable. This corresponds to the PLs difference between the system operation under normal and stressed conditions. As shown in Table II, for the stressed conditions cases, the PL columns correspond to the total system power levels increase capability if the system is assumed to operate under normal conditions, but having as CTs for every contingency the corresponding CCTs of the stressed cases. For example, for the

TABLE I
CCT VALUES FOR CASE STUDY 1A

Contingency No.	Normal Conditions (msec)	Stressed Conditions (msec)
1	172	172
2	79	79
3	125	125
4	196	196
5	219	219
6	188	188
7	141	141
8	242	242
9	297	297
10	219	219
11	219	219
12	266	266

TABLE II
CCT AND PL VALUES FOR CASE STUDY 1B

Contingency No.	Normal Conditions	Stressed Conditions			
		CSS		ESS	
		CCT (msec)	Δ PL (MW)	CCT (msec)	Δ PL (MW)
1	305	281	12.2	258	28.5
2	141	125	20.3	110	41.6
3	141	133	20.3	125	32.6
4	234	203	32.6	196	41.6
5	250	234	20.3	219	37.1
6	196	188	20.3	180	37.1
7	188	172	16.3	157	37.1
8	368	329	20.3	297	37.1
9	414	375	20.3	344	37.1
10	258	250	16.3	242	24.4
11	258	250	12.2	242	24.4
12	352	329	16.3	313	28.5

first contingency, the CT = 281 ms corresponds to the stability limit of the stressed system, whereas, if the system operates under normal conditions and the CT is kept constant (281 ms), the stability limit is reached if the total generation is increased by 12.2 MW (and, accordingly, the demand, but losses have to be taken into account). This shows the system's further stress withstanding capability which is lost when the system is already stressed. It has to be noted that this is not calculated for the summed type OELs utilization cases, since normal and stressed conditions' CCT values match and, as a result, any potential increase in total power levels under normal conditions leads to instability for every contingency, since the system has already reached its stability limit. The tolerance used (i.e., the total PL difference between an unstable and a stable simulation) for the PLs calculation is 5 MW [27].

C. Test System 2: 68-Bus, 16-Machine System

Since the OELs of takeover type have been proven to have a high impact on the stability margin of the previous system, both CSS and ESS schemes were tested in the context of a larger power system. In this case, a modified version of the 68-bus, 16-machine system was used, shown in Fig. 6, where simple static AVRs were used in order to be compatible with the utilization of OELs of takeover type. Also, power system stabilizers (PSSs) were not included in the analysis. The system was initialized for the operating conditions as specified in [19]. The data concerning the AVRs used and the OELs initialization are listed in Appendix B.

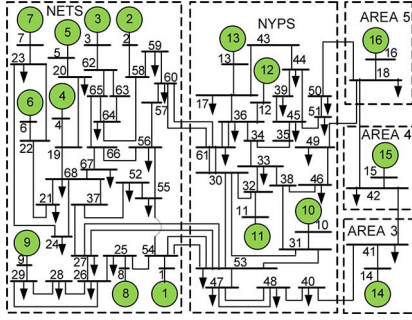


Fig. 6. Test System 2: 68-bus, 16-machine system [26]

TABLE III
CONTINGENCIES LIST FOR THE 16-MACHINE SYSTEM

Contingency No.	Faulted Bus	Tripped Line
1	23	23-22
2	23	24-23
3	22	23-22
4	62	63-62
5	62	65-62
6	25	25-54
7	25	26-25
8	58	58-57
9	58	59-58
10	29	29-28
11	29	29-26
12	54	55-54
13	54	54-53
14	54	25-54

Dynamic simulations were carried out under two conditions; considering constant impedance loads, as in [19], and considering a mixture of constant impedance and composite loads, in order to make the case more realistic. The data for composite loads are based on [20] and are listed in Appendix B. Moreover, the machines whose OELs were assumed to operate during the transient period are the ones connected to buses 1, 6, and 7, according to the same logic as in Test System 1. In the context of this system, only one generator's OEL operates in each case study. Furthermore, a contingencies list was created for this system, creating faults close to generator buses (as previously explained) and the fault clearing is associated with line tripping. Since the generators whose OELs' impact examined are located in the NETS area, faults applied in this particular area have only been considered. The contingencies list is shown in Table III.

The results are shown in Figs. 7 and 8 for the constant load cases. Figs. 9 and 10 are for the cases where there are composite loads in the system. Regarding PLs calculation, the tolerance used (i.e., the total PL difference between an unstable and a stable simulation) is 100 MW. The barcharts clearly illustrate the OEL operation effect on system stability limits for both cases and schemes, when each of the considered OELs operate.

IV. STRESSED CONDITIONS IDENTIFICATION

A. Bad Data Detection Based Methodology

It has been clearly shown that the OEL operation during the transient period after an event occurrence is able to lower system transient stability margins. Therefore, it is crucial to timely identify the OEL activation during the system operation, in order for the operators to act in a way to lower system stress. Here, a dynamic state estimation (DSE) based approach is proposed. More

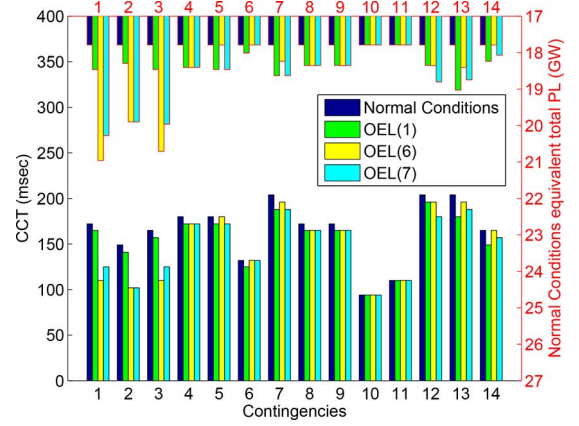


Fig. 7. CCT values for all contingencies, comparing normal to stressed conditions operation, and the corresponding normal conditions PLs, for the CCTs values listed. The loads are of constant impedance type and the OELs are of takeover type, under CSS scheme.

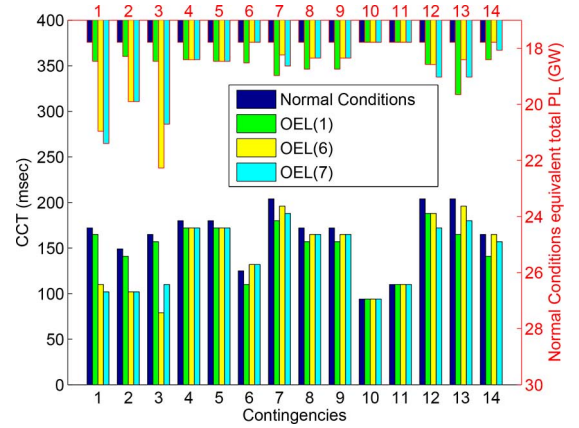


Fig. 8. CCT values for all contingencies, comparing normal to stressed conditions operation, and the corresponding normal conditions PLs, for the CCTs values listed. The loads are of constant impedance type and the OELs are of takeover type, under ESS scheme.

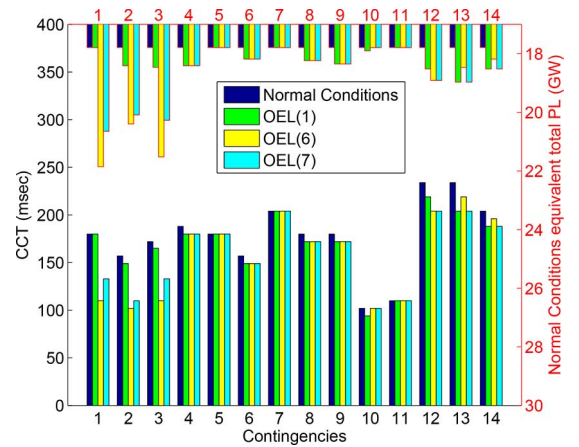


Fig. 9. CCT values for all contingencies, comparing normal to stressed conditions operation, and the corresponding normal conditions PLs, for the CCTs values listed. Composite loads have been considered in some parts of the system and the OELs are of takeover type, under CSS scheme.

specifically, based on the assumption that operators are able to have knowledge about the dynamic model of the system, the system states can be accurately estimated through Unscented

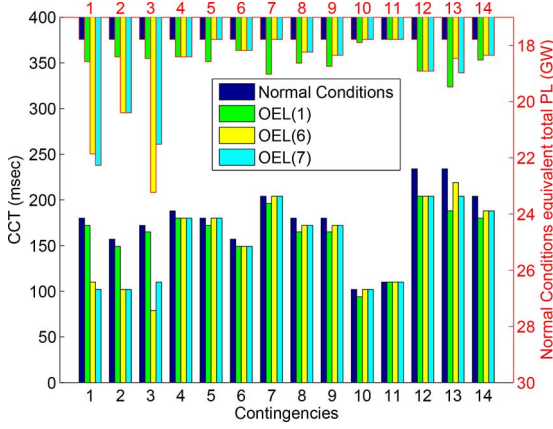


Fig. 10. CCT values for all contingencies, comparing normal to stressed conditions operation, and the corresponding normal conditions PLs, for the CCTs values listed. Composite loads have been considered in some parts of the system and the OELs are of takeover type, under ESS scheme.

Kalman filtering (UKF), since this method reveals highly accurate results in the context of highly nonlinear dynamic systems [32]. Considering as measurements the voltage magnitudes and phases of all buses and the active and reactive outputs as well as the excitation voltages of all system machines, transmitted via PMUs, the system states are able to be quickly estimated through the UKF algorithm [32]. The E_{fd} measurement has been enabled by PMUs released in 2006 [33], [34]. Such implementations have already been reported in the literature [26], [35].

The notion behind the application of this method in this paper is that the OEL operation can be detected without explicit knowledge of the excitation limits and, generally, the OEL model. Here, the OEL activation is identified through the bad data detection procedure. The indicator used is the innovation ratio (λ), defined as the ratio between the deviation of the actual from the predicted measurements and the standard deviation, which is bounded when the system operates as normal without any bad data presence [26], [34], [36].

This stressed system indicator is given by the following [26], [34], [36]:

$$\lambda_{k,i} = \frac{z_{k,i} - \hat{z}_{k,i}}{\sqrt{P_{z_{k,i}}}} \quad (11)$$

where $z_{k,i}$ and $\hat{z}_{k,i}$ are the actual and the predicted i th measurements at the k th time step, and $P_{z_{k,i}}$ is the covariance corresponding to this measurement at this particular time step. Under normal system operation, without any bad data presence, this variable remain bounded for all measurements. The bad data detection procedure is based on testing whether the rule $|\lambda_{k,i}| < \lambda_{\max}$ is respected. The value of $\lambda_{\max}$ depends on the system. In the context of OEL operation identification is that, without explicit knowledge of OEL activation, this will be reflected to primarily the excitation voltage measurement of the relevant machine since the OEL operation dramatically affects E_{fd} of the relevant machine.

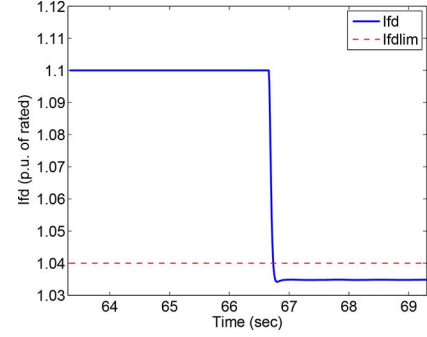


Fig. 11. I_{fd} curve of Gen. 1 as simulated for Test System 1.

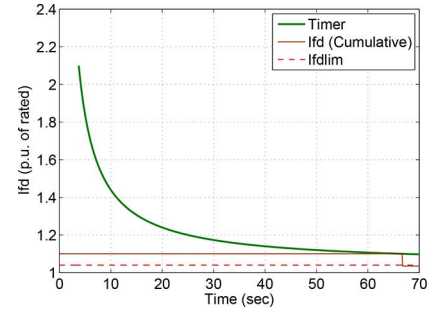


Fig. 12. Cumulative I_{fd} curve of Gen. 1 with respect to OEL time curve for Test System 1.

B. Test System 1: 9-Bus, 3-Machine System

The above concept was implemented in the context of the 9-bus, 3-machine system. An OEL of takeover type was used, designed according to the ESS scheme. The initial field current value of Gen. 1 is $I_{fd0} = 1.1$ p.u., whereas the initial timer output value is -0.2 . Hence, even though OEL's timer has already detected overexcitation, the system operates as normal, but the timer has started counting down. Assuming constant overexcitation, with $I_{fd} = 1.1$, this means that the initial timer output used here (-0.2) corresponds to 63.33 s of constant overexcitation, and the overexcitation limiter is activated at the time instant $t_{act} = 66.67$ s, which corresponds to 3.34 s of our simulation. The I_{fd} curve of Gen. 1 is shown in Fig. 11, whereas, for illustration purposes, the cumulative I_{fd} curve, with respect to the OEL timer allowance is shown in Fig. 12. The DSE procedure is based on the UKF discrete (12)–(15) as shown in Appendix A. The standard deviation regarding the process and measurement noise for all states and measurements, respectively, is assumed to be 10^{-6} . For a time period of 6 seconds, the innovation ratios were calculated for all measurements, illustrated in Fig. 13. It can be clearly noticed that, as assumed, the OEL activation has a high effect on excitation voltage measurements of Gen. 1, as indicated by their innovation ratio, having the greatest deviation from the normal conditions value.

C. Test System 2: 68-Bus, 16-Machine System

The UKF based estimation procedure was implemented in the context of the 68-bus, 16-machine system. In this case, an OEL of takeover type was used, designed according to CSS

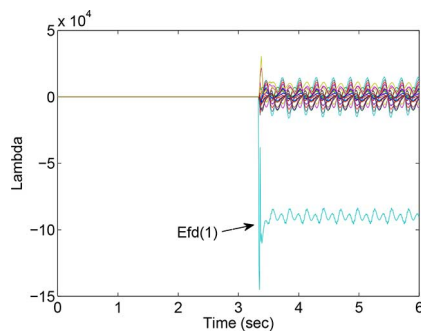


Fig. 13. UKF based innovation ratios for Test System 1.

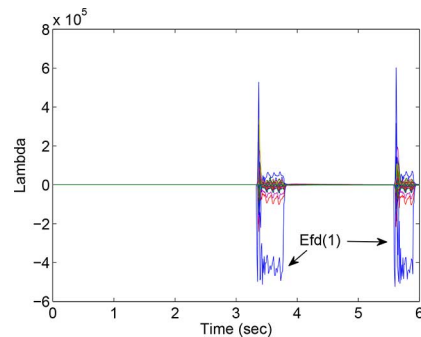


Fig. 14. UKF based innovation ratios for Test System 2.

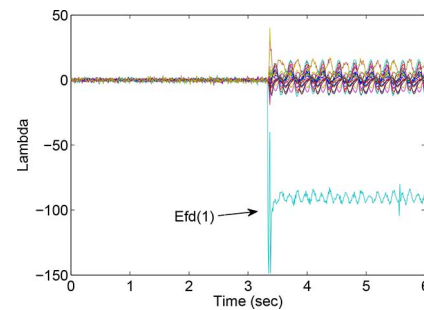


Fig. 15. UKF based innovation ratios subjected to high noise for Test System 1.

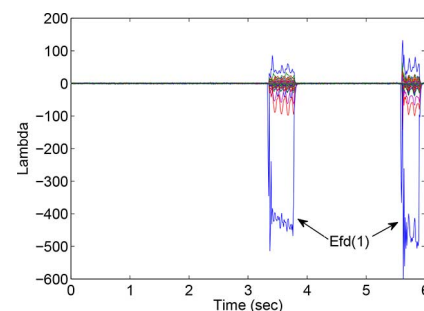


Fig. 16. UKF based innovation ratios subjected to high noise for Test System 2.

scheme. This OEL is part of the excitation system of Gen. 1. The same pattern as above was followed, considering as initial conditions $I_{fd0} = 1.1$ p.u., whereas the initial timer output value is -0.2 . The discrete UKF equations are modified compared to Test System 1, since here the subtransient model of generators is used. These equations can be found in [26]. Regarding the UKF noise data the same assumptions were made as the Test System 1 is concerned. In Fig. 14 the OEL detection indicators are depicted, validating the assumption about OEL operation's effect primarily on excitation voltage measurements of Gen. 1.

D. Sensitivity to Noise

The application of this OEL operation indicator has been proven to be successful regarding the previous test systems, but both cases are based on the assumptions that system modeling approximations and integration errors are very low and, at the same time, PMU measurements are characterized by high accuracy. However, in practice the noise standard deviations can be higher. According to the IEEE Standard C37.118.1-2011, the basic time synchronisation accuracy is $0.2 \mu s$ [37], and, therefore, this is translated to phase measurement error around ± 0.08 mrad, for a 60-Hz system. Furthermore, the power and voltage magnitude measurements are limited by the accuracy of the instrument transformers [38], and according to IEEE Standard C57.13-2008 the instrument transformers' accuracy lies between 0.1% and 0.3% [39].

Taking these into account, the previous case studies were revisited, assuming standard deviation of 10^{-3} regarding system states (process noise), and 10^{-3} for voltage magnitude, excitation voltage and active and reactive power measurements, whereas 10^{-4} for phase voltage measurements (measurement noise). The results are depicted in Figs. 15 and 16 for Test

Systems 1 and 2, respectively, validating the assumptions that OEL operation has the greatest impact on the innovation ratios of the excitation voltage measurements of Gen. 1.

E. Sensitivity to Load Variation and Load Modeling Inaccuracies

The robustness of the proposed OEL operation identification method is also tested with respect to load variations during the simulation. In both systems load increase was assumed, designed as a ramp, having a constant rate of 10 MW/min for Test System 1, and 100 MW/min for Test System 2. For this particular case, synchronous machines' governor and turbine dynamics were included in system modeling, in order for the machines to follow the load changes. For all the machines, non reheat steam turbines were used [20], whose parameter values are listed in Appendix B. The governor and turbine discrete equations, incorporated in the UKF algorithm, are the (16), as shown in Appendix A. Furthermore, in this case, the OEL detection method was tested with respect to the same low and high noise values, as considered in the previous sections. The results regarding Test System 1 for low and high noise values are illustrated in Figs. 17 and 18, respectively, and the ones for Test System 2 are depicted in Figs. 19 and 20 for low and high noise values, respectively. The effect of OEL activation of Gen. 1 on the innovation ratios of the excitation voltage measurements can be clearly noticed.

It is interesting to test the effectiveness of the method when there are load modeling inaccuracies in the context of UKF algorithm. Thus, the two OEL operation detection cases are reimplemented, assuming that some load buses are characterized by composite loads (having values $a = 1.5$, $b = 3.2$) at bus 6 for Test System 1 and at buses 18, 23, 33, 52, and 55 for Test System

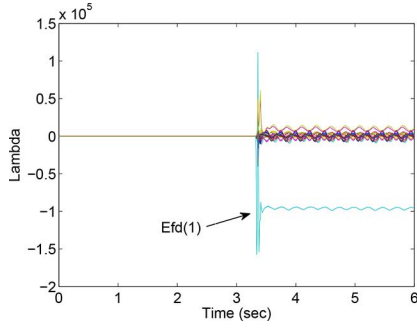


Fig. 17. UKF based innovation ratios subjected to low noise values during load changes for Test System 1.

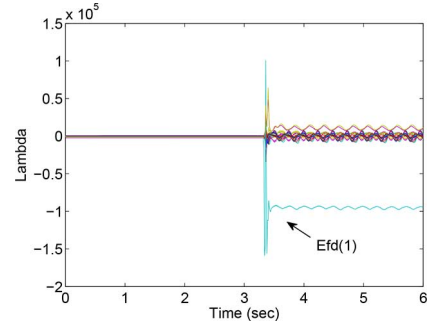


Fig. 21. UKF based innovation ratios subjected to low noise values during load changes considering load modeling inaccuracies for Test System 1.

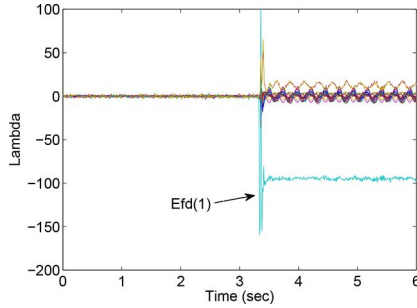


Fig. 18. UKF based innovation ratios subjected to high noise values during load changes for Test System 1.

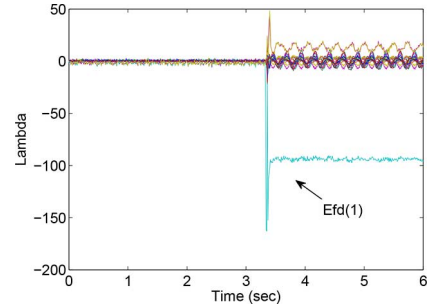


Fig. 22. UKF based innovation ratios subjected to high noise values during load changes considering load modeling inaccuracies for Test System 1.

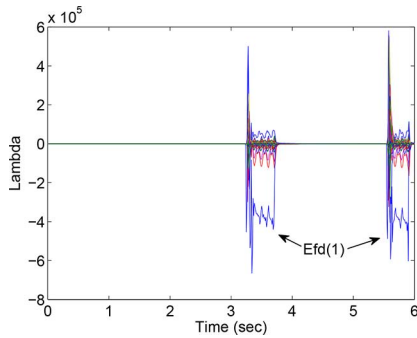


Fig. 19. UKF based innovation ratios subjected to low noise values during load changes for Test System 2.

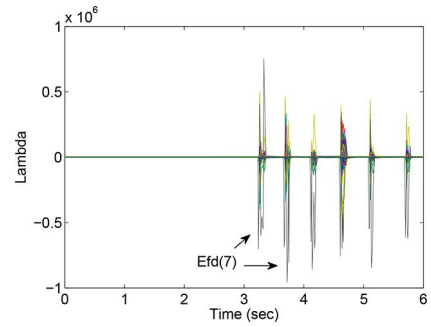


Fig. 23. UKF based innovation ratios subjected to low noise values during load changes considering load modeling inaccuracies for Test System 2.

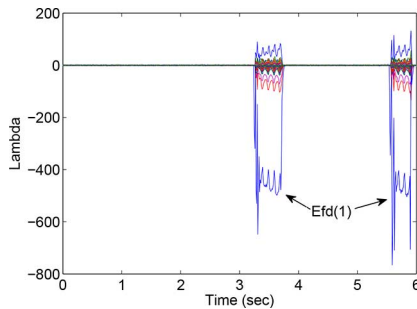


Fig. 20. UKF based innovation ratios subjected to high noise values during load changes for Test System 2.

2, whereas the operator has assumed constant impedance load models in these buses. It has to be noted that, here, regarding Test System 2, the OEL of Gen. 7 was assumed to be activated, since the inaccurately modeled load bus 23 is very close

to this machine and the purpose is to check whether this affects the excitation voltage measurement innovation ratio. Triggering system dynamics in order for load dynamics differences to be present, load increase was assumed, designed as a ramp, having the same values as assumed in the previous load variation case. The results are shown in Figs. 21 and 22 concerning Test System 1 for low and high noise values, respectively, and in Figs. 23 and 24 regarding Test System 2 for low and high noise values, respectively. It can be figured out that the OEL detection method is again robust.

V. CONCLUSION

The impact of the operation of overexcitation limiters on transient stability assessment has been demonstrated. This influence on power system stability margin highly relies on the way OELs are modeled, revealing different security limits, expressed as critical clearing time values and power limit differences, for a

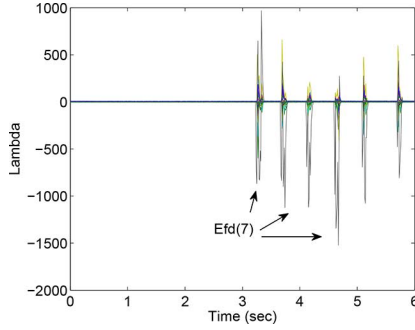


Fig. 24. UKF based innovation ratios subjected to high noise values during load changes considering load modeling inaccuracies for Test System 2.

variety of cases, considering different types of voltage regulators and loads. This OEL activation impact on angle stability margin has been tested in both a small and a large-scale system model, in order to manage to simulate scenarios reflecting real life cases. In order for the operators to be enabled to identify such overexcitation limit crossing cases, an Unscented Kalman filtering based dynamic state estimation scheme has been proposed. This helps the OEL operation to be detected, for cases when operators do not have explicit knowledge of synchronous generators' actual capability limits.

This suggested scheme is another step forward towards the enhanced accuracy of DSA based power system stability margin estimation, which is crucial in modern stressed power systems. The methodology, showing the difference in power system stability margin under stressed conditions, will be useful for additional purposes, such as identifying areas which are benefited by excitation system enhancements or load modeling accuracy upgrade. Future research plans include the dynamic state estimation algorithm adaptation to the OEL activation in order to further increase the accuracy of estimation.

APPENDIX A

DISCRETE DAEs FOR TEST SYSTEM 1

The discrete DAEs for the transient model of a power system are given by (12)–(16):

$$\begin{aligned}\delta_i(k+1) &= \delta_i(k) + T_0\omega_b(\omega_i(k) - 1); \\ \omega_i(k+1) &= \omega_i(k) \\ &+ (T_0/(2H_i))(T_{mi}(k) - T_{ei}(k) - D_i(\omega_i(k) - 1));\end{aligned}\quad (12)$$

$$\begin{aligned}E'_{qi}(k+1) &= E'_{qi}(k) \\ &+ (T_0/T'_{d0i})[E_{fdi}(k) - E'_{qi}(k) + (X_{di} - X'_{di})I_{di}(k)]; \\ E'_{di}(k+1) &= E'_{di}(k) \\ &+ (T_0/T'_{q0i})[-E'_{di}(k) - (X_{qi} - X'_{qi})I_{qi}(k)]; \\ E'_{dci}(k+1) &= E'_{dci}(k) \\ &+ (T_0/T'_{ci})[-E'_{dci}(k) - (X'_{qi} - X'_{di})I_{qi}(k)];\end{aligned}$$

where $T_{ei}(k)$, $I_{di}(k)$ and $I_{qi}(k)$ are algebraic functions of $E'_{di}(k)$,

$E'_{qi}(k)$, $V_i(k)$, $\theta_i(k)$ and $\delta_i(k)$, and are given by :

$$\begin{aligned}T_{ei}(k) &= E'_{di}(k)I_{di}(k) + E'_{qi}(k)I_{qi}(k) \\ &+ (X'_{di} - X'_{qi})I_{di}(k)I_{qi}(k);\end{aligned}$$

TABLE IV

OELs, STATIC AVRS, GOVERNORS, TURBINES, AND COMPOSITE LOADS DATA

OELs:				
$S_1 = 1$	$K_1 = -4$	$K_2 = 0.1$	$K_r = -1$	
$L_1 = -4$	$T_x = 10sec$	$I_{fdlim} = 1.04$	$I_{fd0} = 1.06$	
Static AVRs:				
$K_A = 200$ (Test System 1)		$K_A = 10$ (Test System 2)		
$T_E = 0.01sec$				
Governors & Turbines:				
$R_{gov} = 0.05$	$T_G = 0.2s$	$F_{HP} = 0.3$		
$T_{RH} = 7sec$	$T_{CH} = 0.3sec$			
Composite Load cases:				
$a = 1.3, b = 3.1$ for load buses: 18, 21, 24, 29, 41, 42, 53, 61, 68				
$a = 1.5, b = 3.2$ for load buses: 17, 25, 26, 28, 33, 36				

$$X'_{di}I_{di}(k) - R_{si}I_{qi}(k) + E'_{qi}(k) - V_i(k)\cos(\theta_i(k) - \delta_i(k)) = 0;$$

$$\begin{aligned}X'_{qi}I_{qi}(k) \\ + R_{si}I_{di}(k) - E'_{di}(k) - V_i(k)\sin(\theta_i(k) - \delta_i(k)) = 0;\end{aligned}\quad i = 1, 2, \dots, M. \quad (13)$$

$$\begin{aligned}E_{fdi}(k+1) &= E_{fdi}(k) \\ &+ (T_0/T_{Ei})[K_{Ai}(V_{refi} - V_i(k)) - E_{fdi}(k)];\end{aligned}\quad i = 1, 2, \dots, M. \quad (14)$$

$$(I_{qi}(k) + jI_{di}(k))e^{j\delta_i(k)} = \mathbf{Y}_i(k)\mathbf{V}(k);$$

where $\mathbf{Y}_i(k)$ is the i^{th} row of $\mathbf{Y}(k)$, and $i = 1, 2, \dots, M$.

$$(P_{Li}(k) - jQ_{Li}(k)) + V_i(k)e^{-j\theta_i(k)}(\mathbf{Y}_i(k)\mathbf{V}(k)) = 0;$$

where $\mathbf{Y}_i(k)$ is the i^{th} row of $\mathbf{Y}(k)$, and

$$i = (M+1), (M+2), \dots, N. \quad (15)$$

$$\begin{aligned}x_{govi}(k+1) &= x_{govi}(k) \\ &+ (T_0/T_{Gi})[L_{refi} - (1/R_{govi})(\omega_i(k) - 1) - x_{govi}(k)]; \\ x_{tbi}(k+1) &= x_{tbi}(k) + (T_0/T_{CHi})[x_{govi}(k) - x_{tbi}(k)]; \\ x_{rhi}(k+1) &= x_{rhi}(k) \\ &+ (T_0/T_{RHi})[x_{tbi}(k) - x_{rhi}(k)]; \\ T_{mi}(k) &= (1 - F_{HPi})x_{rhi}(k) + F_{HPi}x_{tbi}(k);\end{aligned}\quad i = 1, 2, \dots, M. \quad (16)$$

APPENDIX B

OELs, STATIC AVRS, GOVERNORS, TURBINES, AND COMPOSITE LOADS DATA

See Table IV at the top of the column.

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Georgios Anagnostou (S'13) was born in Athens, Greece. He received the diploma in electrical and computer engineering from the National Technical University of Athens (NTUA), Athens, Greece, and the M.Sc. degree in sustainable energy futures from Imperial College London, London, U.K., in 2011 and 2012, respectively. He is currently pursuing the Ph.D. degree in the Electrical and Electronic Engineering Department of Imperial College London.

His current research interests include power system dynamics and control, dynamic security assessment, dynamic state estimation, and renewable energy based generation. Mr. Anagnostou is a member of the Technical Chamber of Greece.



Bikash C. Pal (M'00–SM'02–F'13) received the B.E.E. (with honours) degree from Jadavpur University, Calcutta, India, the M.E. degree from the Indian Institute of Science, Bangalore, India, and the Ph.D. degree from the Imperial College London, London, U.K., in 1990, 1992, and 1999, respectively, all in electrical engineering.

Currently, he is a Professor in the Department of Electrical and Electronic Engineering, Imperial College London, London, U.K. His current research interests include state estimation, power system dynamics, and flexible ac transmission system controllers.