Impact of Load Flow and Controller Parameters
on the Electromechanical Wave Propagation in Power Systems

A. Semerow, L. Muth and M. Luther

Institute of Electrical Energy Systems
Friedrich-Alexander-University Erlangen-Nuremberg
Cauerstr. 4, 91058 Erlangen, Germany
e-mail: anatoli.semerow@fau.de

Abstract. In order to comprehend the global behaviour of a power system during significant disturbances, it is essential to understand the basic mechanisms of the simultaneous acceleration of generators as well as the electromechanical wave propagation. Both effects immediately occur as a consequence of events, such as outages and switching operations. This paper contributes to the fundamental understanding of both phenomena, deriving them from theory and analysing the dependencies of the electromechanical wave propagation speed with regard to the indirect impacts by means of simulation in a test power system. The objective of the analysis is to point out the sensitivity of the propagation speed for different load flow cases and varying generator controller parameters. Thereby, the parameters are varied within a certain range considering practical restrictions. The results show a significant impact of the load flow direction on the wave speed, while the modification of most of the controller parameters has a negligible effect.

Key words: Simultaneous Acceleration, Electromechanical Wave Propagation, Propagation Speed, Generator Controller Impact, Load Flow Impact.

1. Introduction

The dynamic behaviour of existing power systems is dominated by generators, even though big efforts are made to promote converter based infeed from renewable energy sources. Among other effects, the generators provide a certain short-circuit level and inertia, which are both mandatory for a stable power system operation. Thereby, the inertia of each generator is crucial for the rotor angle and frequency stability of a power system and it characterises the process after disturbances [1].

Significant incidents in power systems can be effectively analysed by frequency measurements, monitored by means of Wide Area Measurement Systems (WAMS), since the frequencies are mainly determined by generator speeds. Observing such a disturbance, it can be noticed that the consequence of a cause appears in different intensities and partially delayed within the power system [2]. Basically, two observations can be classified as two different phenomena: the simultaneous acceleration of generators and the electromechanical wave propagation [3]. Previous publications such as [3], [4], [5] analytically derive a mathematical description of the wave propagation phenomena by means of a simplified model representation. Moreover, it is also possible to explain the simultaneous acceleration, if practical conditions concerning generator and transformer impedances are assumed [3]. Furthermore, direct impacts on the wave propagation speed as line impedances and generator inertia are identified and already examined in previous works [5], [6].

A better understanding of these phenomena along with the use of a WAMS enable various applications within power system operation, such as wide area control and protection, event localisation and others. Therefore, this paper contributes to the further fundamental understanding of the phenomena. In contrast to previous works, this paper analyses the sensitive dependencies of the electromechanical wave propagation speed with regard to the indirect impacts. These are different load flow cases and varying generator controller parameters. The investigation is performed by means of numerical simulations within a test power system model.

Initially, the fundamentals of disturbance propagation in power systems with respect to both phenomena are shown within the next chapter in order to clarify their differences and dependencies. Within the methodology chapter, a model of a longitudinal test power system and the agreements for the investigation are presented. Subsequently, the sensitivity analysis with regard to different load flow cases and controller parameter variation is carried out and the results are discussed afterwards, before an outlook is given.

2. Fundamentals of Disturbance Propagation in Power Systems

The initial point for the investigation of the phenomena is the torque balance equation for each generator i in a power system using Newton's second law [1]:

$$J_i \frac{d\omega_i}{dt} + D_i \omega_i = T_{t,i} - T_{el,i} \qquad (1)$$

J_i : Total moment of inertia

ω_i : Rotational speed

D_i : Damping constant

$T_{t,i}$: Total mechanical torque

$T_{el,i}$: Electromagnetic torque

A torque imbalance on the right side, for instance caused by a generation outage or load shedding, effects changes in the rotational speed ω_i, considering damping and the total moment of inertia. To apply this equation within a power system analysis, a conversion needs to be done in terms of a detailed definition for the rotational speed

$$\omega_i = \omega_{s,i} + \Delta\omega_i = \omega_{s,i} + \frac{d\delta_i}{dt} \qquad (2)$$

δ_i :   Rotor angle

as well as the basic relationship for power $P = T\omega$, and a more common definition for the total moment of inertia. It contains the nominal apparent power $S_{n,i}$ and inertia constant H_i related to the squared synchronous rotational speed. The result is a swing equation with the balance of the net mechanical power $P_{m,i} = P_{t,i} - D_i\omega_{s,i}$ and the counteracting electrical power [1]:

$$\frac{2H_i S_{n,i}\omega_i}{\omega_{s,i}^2}\frac{d^2\delta_i}{dt^2} + \omega_i D_i \frac{d\delta_i}{dt} = P_{m,i} - P_{el,i} \qquad (3)$$

While this equation describes the interface between the mechanical and the electrical systems, the active power infeed of generator i can be formulated depending on load demand and active power transfer to node j [1]:

$$P_{el,i} = V_i^2 Y_{ii}\cos\theta_{ii} + \sum_{j=1;\,j\neq i}^{N} V_i V_j Y_{ij}\cos\left(\delta_i - \delta_j - \theta_{ij}\right) \quad (4)$$

V_i / V_j :   Voltage at node i / j

Y_{ii} :   Self-admittance at node i

Y_{ij} :   Admittance between nodes i and j

θ_{ii} :   Self-admittance angle at node i

θ_{ij} :   Admittance angle between nodes i and j

Thereby, symmetrical operation is assumed and generator and transformer impedances are minimised [1]. The combination of the two Equations (3) and (4) results in a non-linear differential equation or rather an equation set. It describes an oscillatory system and explains the mechanism of electromechanical interactions in a power system. If an active power imbalance occurs at node i, the generator at this node has to compensate this condition immediately. Therefore, its rotor angle changes according to Equation (3). The changing rotor angle simultaneously influences the power transmission to the adjacent nodes according to Equation (4) and as a consequence, successively influences the active power output of subsequent generators. Along with the delayed changes of rotor angles, also the rotor speed of the generators and the system frequencies vary. This phenomenon of delayed frequency changes and transmitted power demand is called electromechanical wave propagation [4]. The occurring wave propagation speed is much less than that of light [2]. The defined direction of

the electromechanical wave is contrary to the actual direction of the additional power flow in the power system.

In [4], the description of this phenomenon is analytically derived based on the fundamental equations. The result is a continuous wave equation in spatial coordinates. Thereby, system parameters are assumed to be distributed on line length and are given as rated values [4]:

$$\frac{\partial^2\delta}{\partial t^2} + \frac{\omega^2 d}{2h}\frac{\partial\delta}{\partial t} - v^2\nabla^2\delta + \frac{\omega V^2 y_{xy}\cos\theta_{xy}}{2h}\left(\nabla\delta\right)^2$$
$$= \frac{\omega\left(p_m - y_x\cos\theta_x V^2\right)}{2h} \qquad (5)$$

This equation contains the explicit definition of the wave propagation speed [4]:

$$v = \sqrt{\frac{\omega V^2 y_{xy}\sin\theta_{xy}}{2h}} \qquad (6)$$

The equation clearly reveals the parameters, on which the wave propagation speed directly depends. On the one hand, these are the topological properties of the power system, on the other hand the stationary operating points for the rotational speed and the voltage. Previous studies as [5], [6] have analysed the main direct influences in simplified power system models. In contrast to these, this paper focuses on the indirect impacts, particularly: the initial load flow case and the controller parameters of generation units. Both influence the dynamic power system behaviour by affecting the voltage and speed variables within the above equation. Besides, lines and transformers are taken into account using more realistic models than in other studies. Loads are considered as constant impedances so that their behaviour has an impact on the wave propagation speed as well.

Considering more realistic conditions for generator and transformer impedances, the initial description of the electromechanical propagation has to be extended by the mechanism of simultaneous acceleration in order to consider realistic system behaviour. Due to the non-continuity of node voltage angles, in contrast to rotor angles of generators, a voltage angle profile arises on a local imbalance in a power system. As a consequence, the electrically nearest generators immediately compensate the imbalance in common and accelerate or decelerate. The electrically nearer the generator is located to the incident, the stronger is its relative contribution to the active power compensation assuming similar dimensioning. Subsequently, the above described mechanism of electromechanical wave propagation arises in a less pronounced form. Figure 1 exemplarily shows the different behaviour of generator speed due to a load step in a longitudinal power system with similar generation units at each node, considering and minimising the generator and transformer impedances. The blue curves illustrate the case minimising the impedances and therefore, the pure electromechanical wave propagation. As it can be seen, the first generator in the chain instantly has to compensate the entire power imbalance and there-

fore, it decelerates intensively. As a consequence, the second generator starts to decelerate moderately with regard to the changing angle difference. The third and the other generators follow successively in a similar manner.

In the more realistic case, shown as yellow curves in Figure 1, it can be seen that all generators instantly contribute to the power imbalance with regard to the distance to the load step location. Hence, the deceleration is significantly less as in the case before. Subsequently, the mechanism of the gradual propagation arises as well.
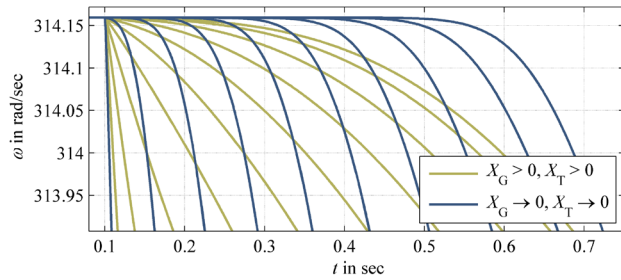

Figure 1: Generator speed with respect to considerations

Another challenge in practice is the exclusive measurement of the electromechanical wave speed, while the system response contains both of the above mentioned phenomena. It is definitely difficult to differentiate the effects in records. Against this background, the generator and transformer impedances are minimised within the later simulative analysis in this paper in order to obtain the exclusive sensitivity to the electromechanical wave.

Different approaches to measure the propagation speed exist, one of which is taken into account in this paper. The method of changing frequencies, which are assumed to be the main indicator of the wave propagation, uses an experience based frequency threshold ε to define the time of wave arrival at the intersections with the individual node frequencies from phasor measurement units (PMU) [7]. Although it is a feasible method, it has some disadvantages, which could be compensated by some newer approaches in future [8].

3. Methodology and Test System

The analysis of the indirect impacts on the electromechanical wave propagation is performed within a simulation model of a longitudinal test power system, as schematically shown in Figure 2, with the simulation tool PSS®Netomac [9]. The nominal voltage at the high-level is 380 kV and at the low-level 10 kV, respectively.
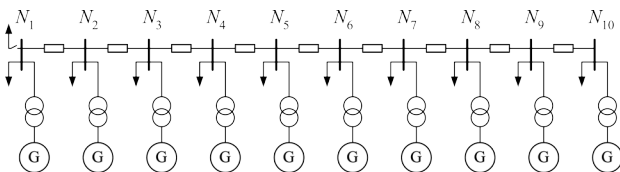

Figure 2: Longitudinal 10 bus test power system

The nodes $N_i, i = 1\dots10$ contain – besides the constant impedance loads and π-model based lines to the adjacent nodes – controlled synchronous generators (gover-

nor (GOV), automatic voltage regulator (AVR), power system stabilizer (PSS)) and the corresponding step-up transformers. The default rated power of each generation unit is given by $S_{N,i} = 600\,\text{MVA}$ for the reference case.

However, the impedances of generators and transformers are dimensioned negligibly in order to accentuate the phenomenon of electromechanical wave propagation. The selection of standard dynamic models for the controllers and the initial parameters is based on [10], [11]. The parameters for the 100 km lines are given in [11], too. Each synchronous generator controls its terminal voltage to 1 pu in all cases. The active power set-point is $P_{0,i} = 475\,\text{MW}$ in the reference case, which complies with the load demand at each node. The reactive power output of generators is automatically adapted with regard to the system conditions. Furthermore, the generator at the first node is defined as slack in order to balance the system. The load flow is varied with regard to the analysed case.

A switchable load at N_1 provides the imbalance to be considered. The transient overloading of the equipment by switching this additional load is accepted, since the focus is on the electromechanical wave propagation.

The evaluation of influences is based on the comparison of the electromechanical wave propagation speed while varying parameters with regard to a reference case at all times. The results for each case are illustrated in a three dimensional diagram showing the electromechanical wave propagation speed for every node. Thereby, the reference case is highlighted. The electromechanical wave propagation speed is determined by means of the identified wave arrival times and is given between two neighbouring nodes, respectively.

Furthermore, the diagrams show the mean wave propagation speed (node number 0) with and without consideration of the first and last speed values. The latter curve is given due to the special status of the two neglected values. Thereby, the speed at the beginning of the chain is relatively high due to the intensive contribution to the compensation of the imbalance of the first synchronous generator. Although the course flattens afterwards in all cases, the last speed value always increases due to the fact that there is no succeeding generator, which absorbs the occurred power demand.

In the first part of the analysis the influence of different load flow cases is investigated. In the reference case, the load is balanced at each node so that minor active power exchange exists. The variation of load flow is realized using constant impedances at the relevant nodes in order to consider the voltage dependency. The second part additionally considers the adjusted set-points of the synchronous generators. In the third part, the reference load flow case is used as a basis for the parameter sensitivity analysis of selected controller parameters. These are chosen with regard to possible adaptations in real power systems and presumed impact from Equation (6).

4. Analysis of Indirect Impacts on Electro-mechanical Wave Propagation Speed

This chapter contains the results of the performed sensitivity analysis and illustrates the identified dependencies of the electromechanical wave propagation speed to the varied power system parameters.

4.1 Load Flow Sensitivity

Table 1 gives an overview of the investigated scenarios within the load flow variation. While the active power set-points of the synchronous generators are not changed within the first two scenarios, they are considered in the last two scenarios by a gradual increase. The load set-points are kept constant within the study.

Table 1: Overview of the analysed load flow scenarios

Scenario	Description
1	Unidirectional load flow from end to end; unaffected generator set-points
2	Bidirectional load flow from the ends to the centre and vice versa; unaffected generator set-points
3	Unidirectional load flow from end to end; affected generator set-points
4	Bidirectional load flow from the ends to the centre and vice versa; affected generator set-points

Furthermore, within the last two scenarios, the rated power of the generation units is increased to 800 MVA in order to satisfy the active power set-point conditions.

Sensitivity, not affecting generator set-points

Using constant impedances at the ends of the power system chain (N_1 and N_{10}), a case specific active power flow is excited within the first investigation according to Table 2. The given active power value indicates the adjusted infeed and demand, respectively.

Table 2: Analysed load flow cases in scenario 1

Load Case	Description of the power flow direction
a	700 MW from N_{10} to N_1
b	500 MW from N_{10} to N_1
c	Reference case
d	500 MW from N_1 to N_{10}
e	700 MW from N_1 to N_{10}

Figure 3 shows the results for the first scenario. The fundamental character of the overall wave speed development occurs as expected within the methodological explanations. The intensity of the effects at the beginning and at the end of the longitudinal power system chain varies with regard to the adjusted load flow case.

As it can also be noticed, the increase of the wave propagation speed is complementary with the increasing power flow in the same direction as the electromechan-

ical wave propagates. Thus, the wave speed decreases with a growing contrary active power flow.
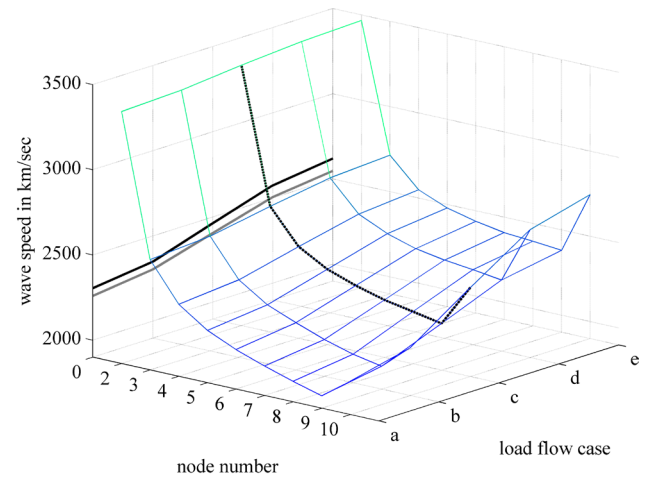

Figure 3: Wave propagation speed depending on the load flow case variation in Table 2

In order to investigate different power flow directions within one electromechanical wave propagation path, the second scenario considers opposite power flows with regard to the chain centre. Table 3 defines the adjusted power flow directions in the power system model.

Table 3: Analysed load flow cases in scenario 2

Load Case	Description of the power flow direction
a	700 MW from N_1 to N_5 and N_{10} to N_6
b	500 MW from N_1 to N_5 and N_{10} to N_6
c	Reference case
d	500 MW from N_5 to N_1 and N_6 to N_{10}
e	700 MW from N_5 to N_1 and N_6 to N_{10}

The conclusions regarding the dependency of the wave speed on the power flow direction drawn in the first scenario can be confirmed in the second scenario, as Figure 4 illustrates. The same relations appear in the respective sections of the power system model.
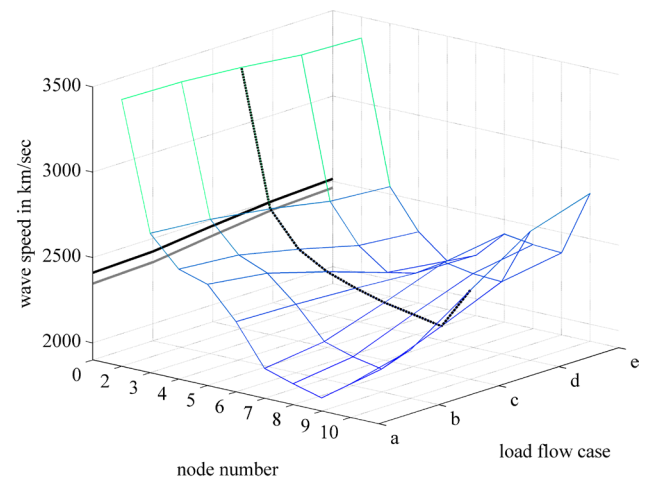

Figure 4: Wave propagation speed depending on the load flow case variation in Table 3

Sensitivity, affecting generator set-points

The dynamic behaviour of synchronous generators depends, inter alia, on their operation-point. Thereby, the active power set-point determines the stationary rotor-angle at a given terminal voltage and therefore, the individual synchronising power. In order to investigate the influence of this coefficient on the electromechanical wave propagation speed, the next two scenarios consider the set-points of the generators within the load flow variation. Table 4 gives an overview on the active power set-point adjustment for the third scenario. Based on a balanced generation and load operation in the centre of the power system, the active power set-points of the adjacent generators are gradually changed so that a desired load flow occurs. In this context, the rated power of the generators has to be increased to 800 MVA to satisfy the stationary active power output.

Table 4: Analysed load flow cases in scenario 3

Load Case	Description of the power flow direction
a	$+50\,\text{MW}$, from N_{10} to N_1
b	$+25\,\text{MW}$, from N_{10} to N_1
c	Reference case
d	$+25\,\text{MW}$, from N_1 to N_{10}
e	$+50\,\text{MW}$, from N_1 to N_{10}

The increased rated power affects the inertia of the generation units. Hence, according to Equation (6), the mean wave propagation speed reduces in general, as it can be observed in Figure 5, as well as in Figure 6 within the next scenario. The dependency's characteristic of scenario 3 is similar to that of Figure 3. The wave speed increases complementary to the power flow in the same direction und decreases with a contrary one.
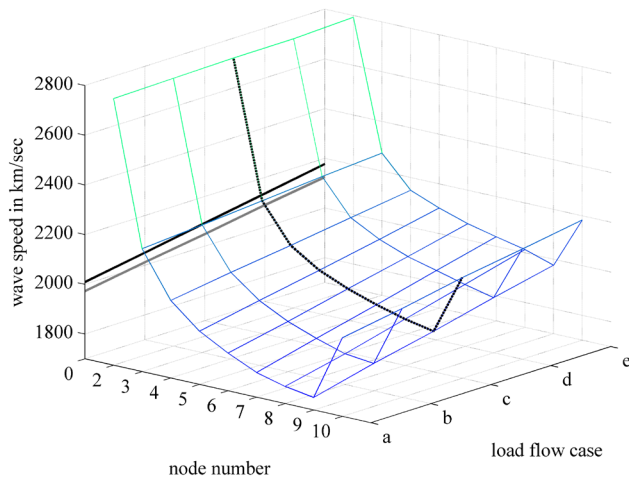

Figure 5: Wave propagation speed depending on the load flow case variation in Table 4

Scenario 4 correspond to scenario 2, considering additionally the active power set-points of the generators. Table 5 shows the description of the analysed load flow cases. In contrast to the third scenario, the balanced nodes are moved to N_3 and N_8 in this scenario in order to get the desired load flow. The gradually adjusted set-

points are oriented to the centre in cases a and b, as well as to the power system ends in cases c and d.

Table 5: Analysed load flow cases in scenario 4

Load Case	Description of the power flow direction
a	$+50\,\text{MW}$, from N_1 to N_5 and N_{10} to N_6
b	$+25\,\text{MW}$, from N_1 to N_5 and N_{10} to N_6
c	Reference case
d	$+25\,\text{MW}$, from N_5 to N_1 and N_6 to N_{10}
e	$+50\,\text{MW}$, from N_5 to N_1 and N_6 to N_{10}

Once again, the relationships which could already be identified in Figure 4 can also be observed in Figure 6, but in a less intensity due to the reduced load flow.
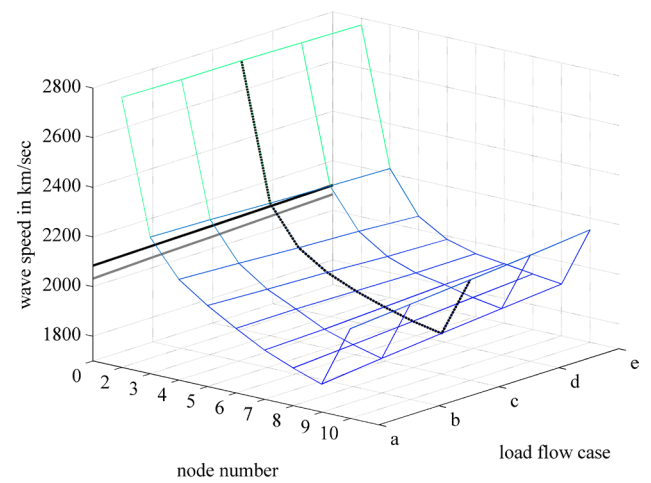

Figure 6: Wave propagation speed depending on the load flow case variation in Table 5

The determined load flow sensitivities for the electromechanical wave speed in the four scenarios show a clear trend independently of the consideration of active power set-points for the generators. An increasing initial active power load flow in the same direction as the wave propagates is complementary to the increase of the wave speed and vice versa. The observations can also be confirmed for different load flow cases in sections.

4.2 Sensitivity to Controller Parameters

In contrast to the load flow cases, the controller parameter variations have no effect on the operating points as long as no limits are exceeded. Instead they influence the dynamic behaviour of the generators. Since the focus of the analysis is on the electromechanical wave propagation speed and its sensitivity on the variation of controller parameters, other effects originating from these variations are not considered in the subsequent analysis. The following parameters are varied, taking into account realistic limits of the generator control and actuators, respectively:

▪ GOV: droop R, and time constants T_{G2} and T_{G3}

▪ AVR: gain K, and time constants T_{A} and T_{B}

▪ PSS: gain K_{S1}

The performed sensitivity analysis for the selected parameters results in the fact that the impact is mostly negligible – except for those, which significantly influence the terminal voltage and thereby the demand of the constant impedance loads. These are notably the gains of the AVR and the PSS. Thus, Figure 7 illustrates the dependency of the wave speed on the PSS gain. The linearized sensitivity can be determined from the mean value with $\Delta v / \Delta K_{S1} = -35.67$ km/sec/pu. An increasing PSS gain at all generators in the longitudinal power system reduces the electromechanical wave speed.
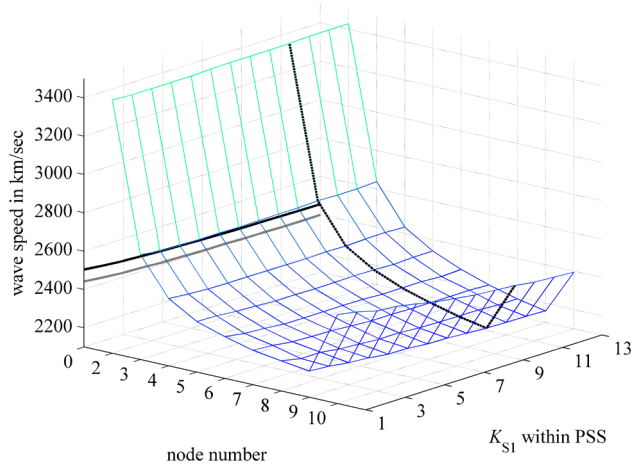

Figure 7: Wave propagation speed depending on the variation of the PSS gain K_{S1}

Figure 8 shows the dependency of the wave speed on the AVR gain. In this case, the linearized sensitivity is determined with $\Delta v / \Delta K = -0.13$ km/sec/pu. Hence, the AVR gain has a complementary effect as the PSS gain.
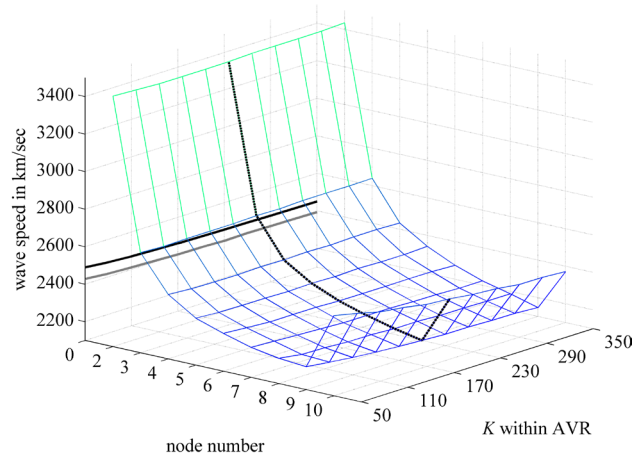

Figure 8: Wave propagation speed depending on the variation of the AVR gain K

As it can be noticed, the determined sensitivities on controller parameter are insignificant with regard to the possible changes and the found influence of load flow cases. Since the controllers have a time-dependent response, which is slow compared to the phenomenon of electromechanical wave propagation, their impact is physically limited.

5. Conclusion and Outlook

Based on a theoretical approach from the dominating origin of power system dynamics – the generators – the paper describes the mechanism of the electromechanical wave propagation as a consequence of imbalances in a power system. The theoretical direct and indirect impacts on the wave propagation speed are explained. Furthermore it is shown that, under practical conditions an additional effect – the simultaneous acceleration of generators – has to be taken into consideration.

Focussing on the electromechanical wave propagation and on the indirect theoretical impacts, the sensitive dependencies for selected changes are investigated. It is clearly determined that the variation of the initial load flow case has a significant influence on the wave propagation speed, while the variation of controller parameters does not considerably affect the wave speed. These findings contribute to the understanding of the physical phenomenon of electromechanical wave propagation and appropriate interactions.

Further research should focus on the enhancement of the method to detect the arrival of the electromechanical wave in order to be able to distinguish the two present phenomena in practice and to gain more precise wave arrival times. Furthermore, the effect of the meshing degree of the grid and the appropriate distribution of inertia on the wave propagation speed can be addressed in order to fulfil practical conditions.

References
[1] J. Machowski, J. W. Bialek, J. R. Bumby "Power System Dynamics: Stability and Control," 2nd ed., Wiley, 2008.
[2] S.-J. S. Tsai, L. Zhang, A. G. Phadke, Y. Liu, "Study of Global Frequency Dynamic Behavior of Large Power Systems," IEEE Power System Conference, New York, 2004.
[3] T. Li, G. Ledwich, Y. Mishra, "Role of Electromechanical Wave Propagation in Power Systems." IEEE PES GM, Vancouver (CA), 2013.
[4] J. S. Thorp, C. E. Seyler, A. G. Phadke, "Electromechanical Wave Propagation in Large Electric Power Systems," IEEE Trans. Circuits Syst. I, vol. 45, no. 6, 1998.
[5] U. Rudez, R. Mihalic, "Understanding the Electromechanical Wave Propagation Speed," IREP Symposium Bulk Power System Dynamics and Control, Rethymnon (GR), 2013.
[6] J. Nutaro, V. Protopopescu, "A New Model of Frequency Delay in Power Systems," IEEE Trans. Circuits Syst. II, vol. 59, no. 11, 2012.
[7] T. Xia et al. "Wide-area Frequency Based Event Location Estimation," IEEE PES GM, Tampa, 2007.
[8] U. Rudez, R. Mihalic, "A Method of Detecting the Time of Arrival for an Electromechanical Wave in Large Power Systems," IEEE PowerTech, Grenoble (FR), 2013.
[9] O. Ruhle, "Modern Power System Analysis Tools," IEEE EPU CRIS, Hanoi (VN), 2011.
[10] ENTSO-E RGCE SG SP&D, "Documentation on Controller Tests in Test Grid Configurations," Technical Report, Brussels (BE), 2013.
[11] A. Semerow, S. Höhn, B. Bauer and M. Luther, "An Innovative Method to Develop Power System Equivalents with Focus on Inter-Area Oscillations and Primary Control Representation," IEEE PowerTech, Eindhoven (NL), 2015.