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Impact of Damper Windings on Unbalanced Steady-State Performance of Synchronous Generator connected to the 500 KV EHV Jamali System

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ABSTRACT

Unbalanced loads, such as unequal voltage magnitudes at the fundamental of both system frequency and phase angle deviation, are inrehent in 500 kV EHV Java-Madura-Bali (or Jamali) System. This crucial unbalanced loads may cause overheating of the machineries including synchronous generators (SG) which is a source of electrical energy generation system. To decrease the unbalance, damper windings are installed in SG. This study is to investigate the performance of three different damper winding configurations of a SG under unbalanced steady-state condition. By the SGs simulator, induced currents of damper windings under the unbalanced steady-state system conditions are measured and analyzed. The value of the generator's inputs is derived through unbalanced Newton-Raphson loadflow analysis on the Jamali System. Clearly that the damper windings have contributed the stability effectively and increased the maximum output. Moreover, there were little lower power angle of the SGs because the damper windings reduced the unbalanced loads.
Keywords: damper windings, 500 kV EHV Jamali System, unbalanced steady state

1. INTRODUCTION

The dynamic behaviors of an unbalanced steady state operating conditions such as unbalanced short-circuits of synchronous generators have received considerable attention [1]. However, the problem of the unbalance during the synchronous generator is connected the grids, which is known as interconnected power system, has not been comprehensively solved [2]. The unbalance in nature comprises unequal voltage magnitudes at the fundamental of both system frequency and phase (or load) angle deviation. Negative sequence current in crucial unbalanced systems may cause overheating of the machineries; zero sequence current may cause improper action of the protective relaying [3-5]. Noted, this is becomes an important issue in interconnected power system.

Many researchers analyze the performance of small signal dynamic of SG connected to the load under any unbalanced operation conditions focus only on the distributed generating case and *single machine infinite bus*. They use many linear and nonlinear models of synchronous generator for steady-state study using different frames of reference including *dqo* [6-10] and *αβo*-coordinates [11] in time [12]. The crucial importance of an appropriate model taking in account dampers which are sometime neglected in those simplified models. Thus, the characteristics of damper windings and their effects on machine dynamics in the electric power system have not yet to be sufficiently clarified. Whereas the damper windings are employed to both increase power output and contribute the stability. The question is "will damper windings do improve dynamic behavior and what kind of damper winding configuration should be employed?"

The study reflects several designs of damper windings installed on synchronous generators which are connected to 500 kV EHV Jamali System. The study was conceded out through the hybrid-method by combination both unbalanced Newton-Raphson loadflow and the synchronous generator simulator based on the *qd0* reference frame of synchronous generator model [13].

This work is firstly gave A brief explanation about the concepts and algorithms involving the unbalanced condition of balanced synchronous generator which is defined on Section 1. Then, Section 2 presents the review concepts and algorithm. The demonstrations are presented on Section 3. Finally, Section 4 presents the results and conclusion.

2. REVIEW CONCEPTS AND ALGORITHMS

The current section describes a brief discussion considering the operation of power system with synchronous generators under unbalanced steady state condition.

A. Steady State Unbalanced Operation

In Indonesia and in several countries around the world, it is common that many large synchronous generators connected to the power grid are usually found in recent power system. The 500 kV EHV Jamali Systems is one of an example. SGs which is a source of electrical energy generation system often operates on unbalanced three-phase loading. That is the stator currents have different amplitudes, and their phase displacement differs from 120^O [14]. According to Fortesque’s transform, these phase currents can be decomposed in positive, negative and zero sequence currents

At unbalanced operation, the armature current presents negative and zero sequence components. The negative sequence components produces magneto-motive force (MMF) that travels at opposite rotor speed, while the zero sequence components produce a zero traveling field in an air-gap and do not interact with the rotor in term of the fundamental component. The positive and negative sequence components produce a net MMF with a sinusoidal variation of its maximum amplitude under and will also appear a sinusoidal variation with a frequency. The speed of the generator consequently will not be constant.

B. Balanced SG with Unbalaned Loads

The balanced three-phase synchronous generator’s model is shown in Fig. 1. It is clear that the generator is driven by the unbalanced voltage inputs; thus:

$$\left.\begin{aligned} V_{ag} &= V_{m1}\ \cos(\omega t - \gamma_1) \\ V_{bg} &= V_{m1}\ \cos\left(\omega t + \tfrac{2}{3}\pi - \gamma_2\right) \\ V_{cg} &= V_{m1}\ \cos\left(\omega t + \tfrac{4}{3}\pi - \gamma_3\right) \end{aligned}\right\} \gamma_1 \neq \gamma_2 \neq \gamma_3 \qquad (1)$$

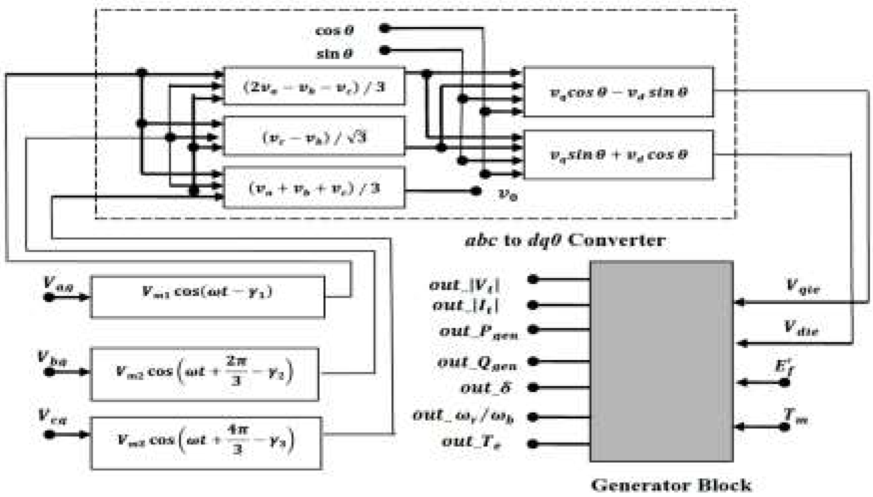


Fig. 1. Balanced generator with unbalanced inputs [15]

The balanced generator model can consist of three stator windings, one rotor winding, and one, two, three or without damper windings. Fig. 2 describes the generator model with two damper windings [16]. The model is based on an ideal concept so the fields produced by the winding currents are assumed to be sinusodally distributed around the airgap and ignores the space harmonics. And also stator slot cause no apprecible variation of any of the rotor winding inductances.

In three axis framework, the model can be written as:

$$\begin{aligned} v_{abc} &= -r_s \cdot i_{abc} + \tfrac{d}{dt}\Psi_{abc} & \qquad v_f &= r_f \cdot i_f + \tfrac{d}{dt}\Psi_f \\ 0 &= r_{kd} \cdot i_{kd} + \tfrac{d}{dt}\Psi_{kd} & \qquad 0 &= r_{kq} \cdot i_{kq} + \tfrac{d}{dt}\Psi_{kq} \end{aligned} \qquad (2)$$

Where i_{kd} and i_{kq} are the currents of direct and tranverse damper windings, Ψ_{kd} and Ψ_{kq} are the total flux of direct and tranverse damper windings, Ψ_{abc} is the stator total flux and Ψ_f is the main field total flux.

Equation (1) can be written in qd reference framework using Park's transformation matrix as.

$$\begin{aligned} v_{qs}^r &= -r_s i_{qs}^r + \frac{\omega_r}{\omega_b}\psi_{ds}^r + \frac{p}{\omega_b}\psi_{qs}^r \\ v_{ds}^r &= -r_s i_{ds}^r + \frac{\omega_r}{\omega_b}\psi_{qs}^r + \frac{p}{\omega_b}\psi_{ds}^r \\ v_{0s}^r &= -r_s i_{0s}^r + \frac{p}{\omega_b}\psi_{0s}^r \qquad v_{kq}^r = -r_{kq} i_{kq}^r + \frac{p}{\omega_b}\psi_{kq}^r \\ v_{kd}^r &= -r_{kd} i_{kd}^r + \frac{p}{\omega_b}\psi_{kd}^r \qquad v_{fd}^r = -r_{fd} i_{fd}^r + \frac{p}{\omega_b}\psi_{fd}^r \end{aligned} \tag{3}$$

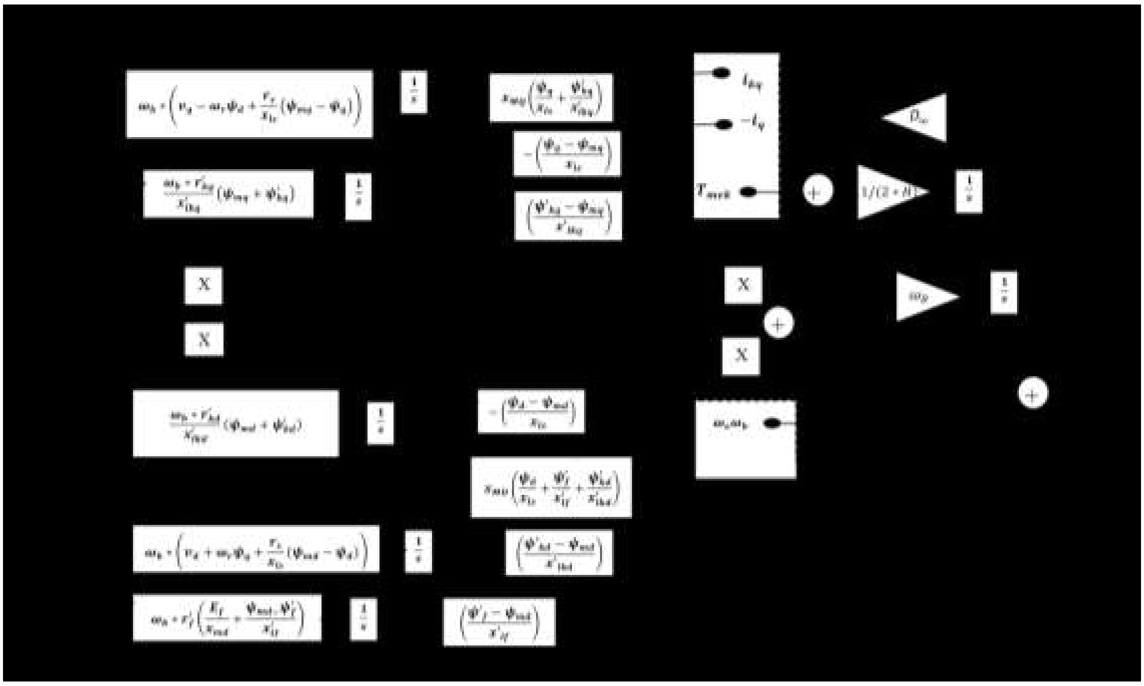


Fig. 2. SG model with damper windings [15]

In these v represents the voltage of windings, I represents the electrical current flowing in the winding, ψ represents the magnetic flux linking the winding, p represents differential operator (d/dt), ω_r and ω_b are angular speed of the rotor refered to a two pole generator and reference angular speed corresponded to the rated frequency, respectively. Since the damping windings are short-circuited, the value of v_{kq}^r and v_{kd}^r are null.

$$\begin{aligned} \psi_{qs}^r &= -x_{ls} i_{qs}^r + x_{mq}\left(-i_{qs}^r + i_{kq}^r\right) \\ \psi_{ds}^r &= -x_{ls} i_{ds}^r + x_{md}\left(-i_{ds}^r + i_{fd}^r + i_{kd}^r\right) \\ \psi_{0s}^r &= -x_{ls} i_{0s} \\ \psi_{kq}^r &= x_{lkq} i_{kq}^r + x_{mq}\left(-i_{qs}^r + i_{kq}^r\right) \\ \psi_{kd}^r &= x_{lkd} i_{kd}^r + x_{md}\left(-i_{ds}^r + i_{fd}^r + i_{kd}^r\right) \\ \psi_{fd}^r &= x_{lfd} i_{fd}^r + x_{md}\left(-i_{ds}^r + i_{fd}^r + i_{kd}^r\right) \end{aligned} \tag{4}$$

Where r_s, r_{kq}, r_{kd}, r_{fd}, x_{ls}, x_{lkq}, x_{lkd}, x_{lfd}, x_{mq} and x_{md} are the electrical fundamental parameters of synchronous generator.

The direct-axis reactance x_d and the quadrature-axis reactance x_q are given by:

$$x_d = x_{ls} + x_{md} \qquad x_q = x_{ls} + x_{mq} \tag{5}$$

The mechanical part of the generator is described by two differential equations as described in:

$$p\delta = \omega_r - \omega_s$$
$$\frac{2H}{\omega_s} p\omega_r = T_m - \left(\psi_d i_{qs} - \psi_d i_{qs}\right) - T_{damp} \quad (6)$$

In (6), H is an inertia constant of the turbine generator set, T_m and T_{damp} are the mechanical and damping torques.

C. Studied System Description

The studied generator is Grati which is one of generating plants of 500 KV EHV Jamali System, shown in Fig. 3. The grid consists of 9 generator nodes such as Suralaya 1 (1,850 MW), Suralaya2 (1,600 MW), Cirata (1000 MW), Muara Tawar (500 MW), Saguling (450 MW), Tanjung Jati B (820 MW), Grati (200), Gresik (298), and Paiton (2,252 MW).

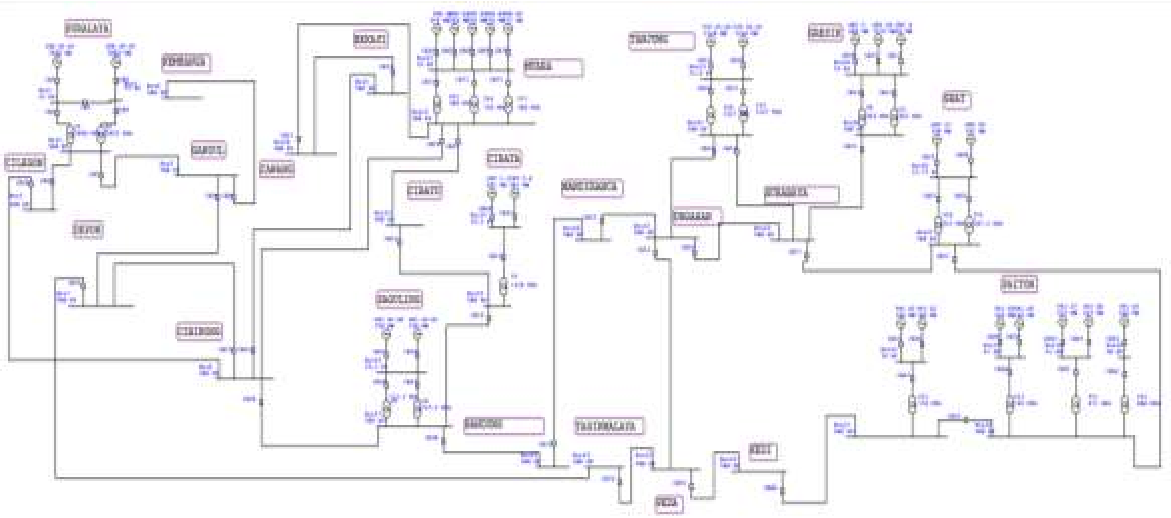


Fig. 3. Location of the test generator in 500 kV EHV Jamali System [15]

Table 1. IBT's Name and Capacity [13]

Region	Bus	Capacity MW	Capacity MVAR
I	Bekasi	730	-260
	Cawang	650	198
	Cibinong	680	378
	Cilegon	289	127
	Gandul	596	-530
	Kembangan	624	220
	Suralaya	248	-37
II	South Bandung	496	334
	Cibatu	634	288
	Cirata	484	138
	Depok	263	37
	Mandirancang	226	69
	Tasik	7	0
III	Pedan	444	222
	Ungaran	490	109
IV	Grati	198	132
	Gresik	193	139
	Kediri	253	118
	Paiton	423	59
	West Surabaya	683	261

It also consists of 21 load or Inter Transformer Bus nodes shown in Table I. The swing bus is Paiton's bus and others are PV buses. Transmission lines use ACSR-556.5 type. System benchmark capacity is 100 MVA.

3. DEMONSTRATION

To study effects damper windings on unbalanced steady state operation of synchronous generator, several simulations were performed under unbalanced Newon-Raphson (NR) loadflow analysis and synchronous generator simulator which based on Matlab/Simulink. Fig. 4 shows the windows Of synchronous generator simulator. The analysis and simulation processes can be described by the block diagram of Fig. 5, in which the role and content of the box simply illustrated a follows:

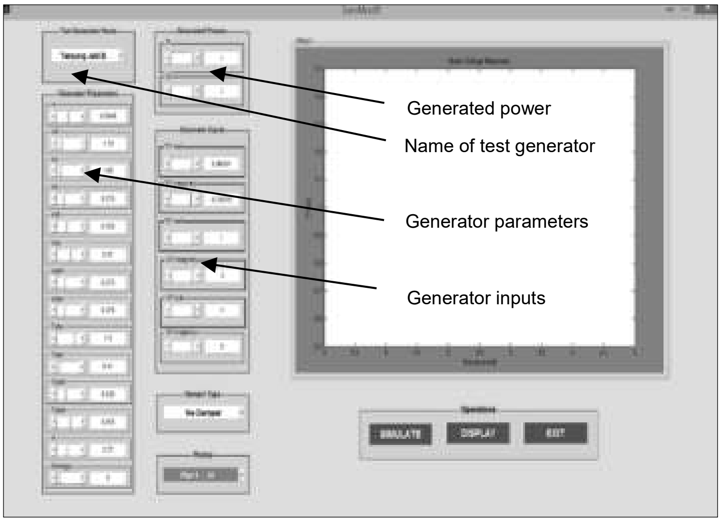


Fig. 4. The windows of synchronous generator simulator [15]

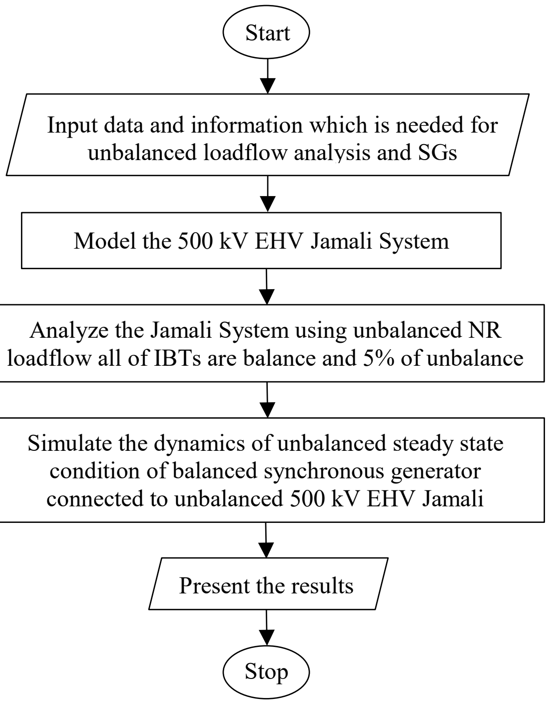


Fig. 5. Research flowchart

A. Grati's Terminal Inputs Calculation

One can get the loadflow calculation results from Fig. 3 that uses unbalanced NR loadflow analysis. Table II presents interphase voltage values of the test generator terminal, balanced and 5% of unbalanced loading condition. It is shown that under unbalanced loads condition, the phase angles of generator terminal voltage are deviated from its balanced value.

Table 2. Voltage Values of Generator Terminals

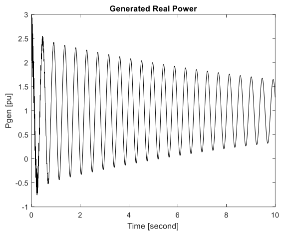
Condition	Phase	Voltage
Balanced loads	*a*	$1\angle -7.7°$
	b	$1\angle 120°$
	c	$1\angle 240°$
5% of unbalanced loads	*a*	$1\angle -8.0°$
	b	$1\angle 120°$
	c	$1\ \angle 240°$

B. Effects Damper Windings on Unbalanced Steady State Performance under Unbalanced Loading

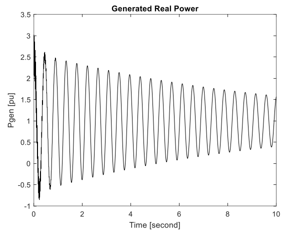
The user friendly of operating the proposed tool for the effects damper windings of the generator under unbalanced loading has been demonstrated by examining the variations of dynamic parameters at different levels of unbalanced load. Its characteristics are presented in Table III. This leads to the following figures which present the steady state condition, balanced and unbalanced loads, of generated active powers and of power angles.

Table 3. Generator ratings and Parameters

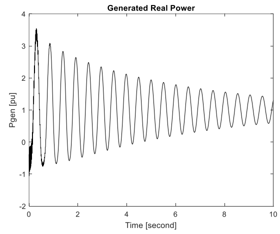
Power	200	MVA	x''_d	0.191	p.u
Voltage	20	kV	x''_q	0.191	p.u
Frequency	50	Hz	T'_{d0}	4.3	p.u
Power factor	0.9		T'_{q0}	0.023	p.u
r_s	0.0019	p.u	T''_{d0}	0.032	p.u
x_d	0,85	p.u	T''_{q0}	0.066	p.u
x_q	0.485	p.u	H	5,6	p.u
x_{ls}	0.120	p.u	d_ω	2	second
x'_d	0.28	p.u			



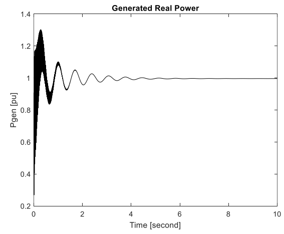
No damper winding



With *d*-axis damper winding

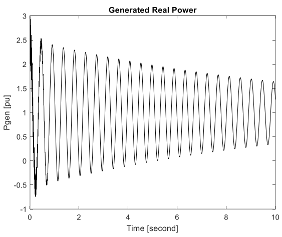


With *q*-axis damper winding

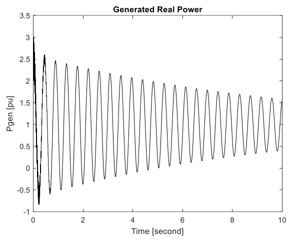


With *dq*-axis damper winding

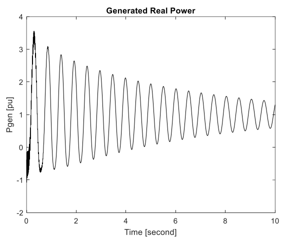
Fig. 6. Simulated balanced load conditions of active powers of generators



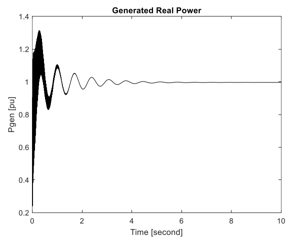
No damper winding



With *d*-axis damper winding



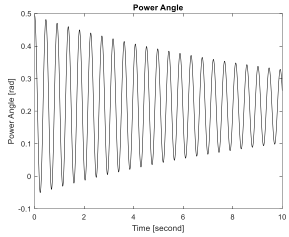
With *q*-axis damper winding



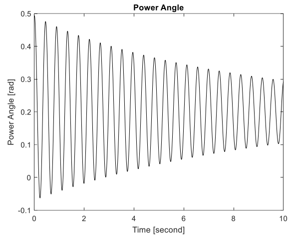
With *dq*-axis damper winding

Fig. 7. Simulated unbalanced load conditions of active powers of generators

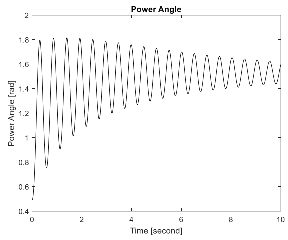
In Fig. (6) and (7), it is seen that utilizing of damper windings on both *d*-axis and *q*-axis will influence on the decreasing of oscillation values of generated active power during steady-state period. Surprisingly, using one damper winding, either on *d*-axis or *q*-axis, will oscillate the dynamic behaviour greater than without using damper winding. By applying *dq*-axis damper winding, the increasing percentage of unbalanced load up to 5% will not influence significantly on greater of generated active power.



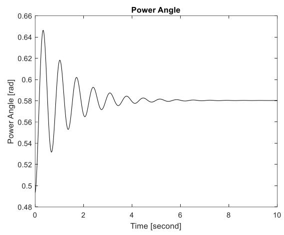
No damper winding



With *d*-axis damper winding



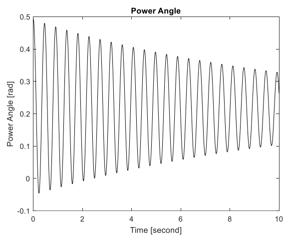
With *q*-axis damper winding



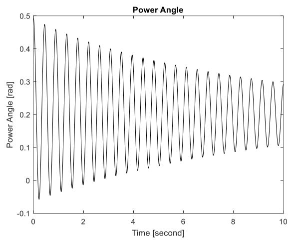
With *dq*-axis damper winding

Fig. 8. Simulated balanced load conditions of power angle of generators

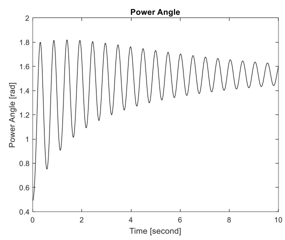
It is seen in Fig. (8) and (9) that employing of damper windings on both *d*-axis and *q*-axis will stabilize the power angle values during steady-state period. Using just one damper winding on *q*-axis, will destroy the dynamic behaviour of power angle during unbalanced loading. By apply *dq*-axis damper winding, the increasing percentage of unbalanced load up to 5% will slightly fluctuate power angle value.



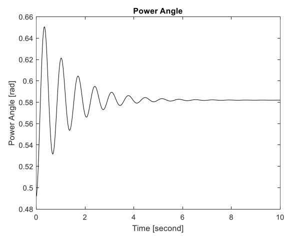
No damper winding



With *d*-axis damper winding



With *q*-axis damper winding



With *dq*-axis damper winding

Fig. 9. Simulated unbalanced load conditions of power angle of generators

4. CONCLUSSION

This paper presents about the impact of damper windings on unbalanced load performance of a synchronous generator connected to 500 kV EHV Jamali. The system model can be represented by the combination between both unbalanced three-phase Newton-Raphson loadflow and the rotor's *qd0* reference frame of synchronous generator.

It is shown that under unbalanced loads condition, the phase angles of terminal generator voltage are deviated from its balanced value. The biggest deviation occurs when the grid operates under balanced load condition

The main conclusion that could be drawn with this study cases are that utilizing of damper windings on both *d*-axis and *q*-axis will influence on the decreasing of oscillation values of generated active power and power angle. The increasing percentage of unbalanced load up to 5% will not influence significantly on both values.

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