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GRID-FORMING/FOLLOWING CONTROL FOR CONVERTERS OF RENEWABLE ENERGY SOURCES

O. Agamalov
Tashlyk Pump Storage Power Plant,
Yushnoukrainsk, Ukraine
e-mail: olegagamalov@gmail.com

Have been proposed the new control framework for converters of renewable energy sources (RES-C), based on choosing their operation mode – grid-forming or grid-following in depends on the dynamic stiffness (DS) of the power system for some bus **i** *(control point), where we can observe arbitrary disturbance. In the proposed RES-C control framework, in cases of small values of DS around bus* **i**, *used the grid-forming control mode of RES-C, and in cases of large values of DS around bus* **i,** *used the grid-following control mode of RES-C. Operation mode of RES-C can be changing in depends on measured DS values for bus* **i** *of a power system.* References 4, figures 2.

Key words: renewable energy sources (RES), dynamic stiffness (DS), grid-forming/following control (GFFC).

In this paper have been proposed the new control framework for converters of renewable energy sources (*RES-C*) that based on the mathematical model of the power system's dynamic stiffness (*DS*).

We have been defining the dynamic stiffness (*DS*) of a power system for some bus i as the ratio of a phasor of complex power deviation ΔS (injections into the bus and power flows out of the bus) [1] to a phasor of a rotor (or load if for tie-line) angle deviation $\Delta\delta$ at bus i where we can observe some disturbance:

$$DS_i(j\omega)=\frac{\Delta S_{gi}-\Delta S_{fi}}{\Delta\delta_i}=\frac{\Delta S_{gi}-\sum\limits_{k=1}^{N}(G_{ik}-jB_{ik})|V_i||V_k|e^{j(\delta_i-\delta_k)}}{\sum\limits_{k=1}^{N}(\delta_i-\delta_k)}, \tag{1}$$

where $\Delta \mathbf{S}_{gi}$ is the phasor the deviations of complex power injections from synchronous machines (*SM*), *RES-C*, and local load into the bus i, $\Delta S_{fi}=\sum\limits_{k=1}^{N}(G_{ik}-jB_{ik})|V_i||V_k|e^{j(\delta_i-\delta_k)}$ is the phasor the deviations of complex power flows out of the bus i into linked buses $k=1...N$ of the power system's grid, $\Delta\delta_i=\sum\limits_{k=1}^{N}(\delta_i-\delta_k)$ is the phasor the deviations of rotor (or load if for tie-line) angles at bus i relative linked buses $k=1...N$ of the power system's grid, V_i, V_k are the voltages at buses i, k; G_{ik} is the conductance between buses i, k; B_{ik} is the susceptance between buses i, k.

So, we have been proposing measuring as magnitudes of changes complex power, and rotor (load) angles for some bus i, but also angular or phase relationship between them. It let us estimate a local power system's inertia around bus i in real-time.

Further, we can consider the Direct component of the dynamic stiffness *DDSi(jω)* that determines how strong a disturbance influencing to the bus i of the power system, and Quadrature component of the dynamic stiffness *QDSi(jω)* that determines the dynamic property of the power system's inertia around bus i at this disturbance

$$DS_i(j\omega)=DDS_i(j\omega)+jQDS_i(j\omega)=$$

$$=\frac{\Delta S_{gi}-\sum\limits_{k=1}^{N}|V_i||V_k|\left[B_{ik}\sin(\delta_i-\delta_k)+G_{ik}\cos(\delta_i-\delta_k)\right]}{\sum\limits_{k=1}^{N}(\delta_i-\delta_k)}+j\frac{\sum\limits_{k=1}^{N}|V_i||V_k|\left[G_{ik}\sin(\delta_i-\delta_k)-B_{ik}\cos(\delta_i-\delta_k)\right]}{\sum\limits_{k=1}^{N}(\delta_i-\delta_k)}. \tag{2}$$

If we directed the phasor $\Delta S_i=\Delta S_{gi}-\Delta S_{fi}$ at X-axis then the phasor $\Delta\delta_i=\sum\limits_{k=1}^{N}(\delta_i-\delta_k)$ will have some lag ξ_i in depends on the system inertia around local bus i. Vector *DSi(jω)* co-directed with phasor $\Delta\delta_i$. Then

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ORCID ID: https://orcid.org/0000-0002-0330-8268

the graphical representation of the power system's dynamic stiffness *DSi(jω)* and their *DDSi(jω)* and *QDSi(jω)* components shown on fig. 1.

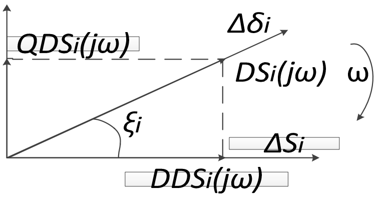

Fig. 1

At electromechanical resonance (low-frequency oscillations) in a power system the *DDSi(jω)* is striving or equal to zero, so the value of *DDSi(jω)* can be used for estimation of power system stability in real-time. For a stable power system for all buses, *i=1…N* *DDSi(jω)* and *QDSi(jω)* are not zero at same frequency of oscillations, and the difference in frequency between zeros of *DDSi(jω)* and *QDSi(jω)* may be referred as the margin of power system stability (if *QDSi(j0)*=0). The *QDSi(jω)* that determines the dynamic property of a power system's inertia around bus *i* at a disturbance may be used for estimation and resilience planning at increasing renewable power mix, and for control *RES-C* in grid-forming/following control (*GFFC*) operation mode. The parameters that need for estimation of *DSi(jω)*, *DDSi(jω)*, *QDSi(jω)* may be calculated (G_{ik}, B_{ik}) or measured (V_i, V_k, $\Delta\delta_i$) with use modern wide-area measurement systems (*WAMS*) [2] and thus the *DSi(jω)*, *DDSi(jω)* and *QDSi(jω)* of a power system may be tracked in real-time for all needed buses *i=1…N*.

Measurement and use of the power system's *DS*, due to its properties, can be used for estimation and resilience planning at increasing renewable power mix on long time intervals. But what is more interesting, based on the DS of a power system, we can design a new control strategy of *RES-C*. As known, in the grid-following mode of *RES-C*, the grid regulates the frequency and the voltage while the *RES-C* stays synchronous and provides a set amount of power simply following the imposed values voltage and frequency [3, 4]. Grid-following *RES-C* utilized a phase-locked loop (*PLL*) to estimate the instantaneous angle of the sinusoidal voltage at the alternating current (*AC*) *RES-C* terminal. So, operating *RES-C* in grid-following mode is only possible if there are other resources that can form stability values voltage and frequency ("stiff" power system) as for example, hydropower, and a grid-following *RES-C* may be simulates as a sinusoidal current source that "follows" the voltage at *AC RES-C* terminal. In the grid-forming mode *RES-C* regulates the voltage magnitude at its terminal, and the frequency to the specific setpoint, as an SM [3, 4], used local decentralized measurements of parameters.

In the proposed control framework for weak *DS* of a power system around bus *i* set in the grid-forming mode operation of *RES-C*, and for strong *DS* of a power system around bus *i* set in the grid-following mode operation of *RES-C*. *RES-C* mode operation can be changing depends on the measured value of a power system's *DS*. If *DS* is less than a tuned threshold (or it's component *QDS*) $DS \le DS_{min}$, $QDS \le QDS_{min}$ then *RES-C* works in the grid-forming operation mode. If *DS* is more than tuned threshold (or its component *QDS*) $DS > DS_{min}$, $QDS > QDS_{min}$ then *RES-C* works in the grid-following operation mode. So, the transition from grid-following to grid-forming *RES-C* operation mode and back is primarily defining as a control problem with feedback on the power system's *DS*, i.e. defining of power system's dynamic properties. Proposed grid-forming/following control (*GFFC*) of the *RES-C* prevents unwanted interaction ("hunting" as for fast-acting excitation systems of synchronous machines (*SM*)) between *RES-C* if they all were in grid-forming mode operation and parallel with *SM*s.

RES-C grid-forming/following control (*GFFC*) included the next main parts/

1. The outer control loop of *RES-C GFFC* include the *DS* controller, which provides the output for adjusting the operation mode of *RES-C* (grid-forming or grid-following) according to a measured changing of *DS* (*ΔDS*) of a power system around bus *i* (current value DS_{cur} or QDS_{cur} relative its threshold value DS_{min} or QDS_{min}) that defined for need *DS* stability margin

$$\Delta DS = DS_{cur} - DS_{\min}, \Delta QDS = QDS_{cur} - QDS_{\min} \tag{3}$$

2. The inner control loop of *RES-C GFFC* include the active *P* and reactive *Q* power controllers, which provide the output voltage-angle and magnitude reference by adjusting the predefined setpoint(s) according to a measured power imbalance, and (*P-f*)/(*Q-V*) droop controls in grid-forming operation mode if $\Delta DS(\Delta QDS) < 0$. Also, inner control loop include the voltage *V* and current *I* controllers, which together with *PLL* measure the amplitude, phase, and frequency of the grid voltage and adapt injected current to feed the grid with the desired values *P*, *Q* at the measured frequency *f* in grid-following mode if $\Delta DS(\Delta QDS) > 0$.

Block diagram of *RES-C* with grid-forming/following control *GFFC* shown on the fig. 2.

Conclusions. In this paper have been proposed the ew control framework for *RES-C* – grid-forming/following control *GFFC* at witch for strong *DS* using grid-following *RES-C* operation mode, and for weak *DS* using grid-forming *RES-C* operation mode that prevents unwanted interactions *RES-C* ("hunting").

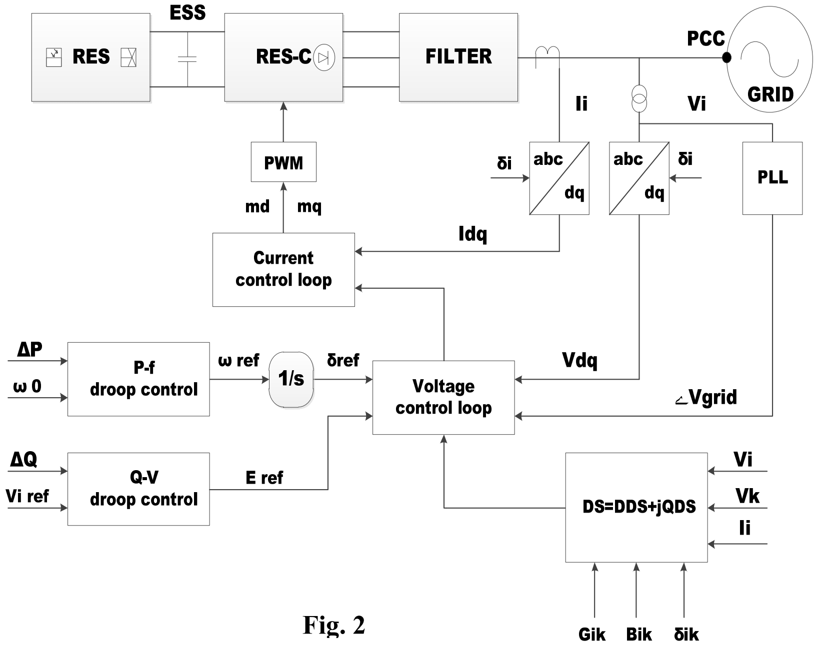

Fig. 2

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КЕРУВАННЯ ПЕРЕТВОРЮВАЧАМИ ВІДНОВЛЮВАНИХ ДЖЕРЕЛ ЕНЕРГІЇ В РЕЖИМІ «МЕРЕЖА-ВЕДУЧИЙ/ВЕДЕНИЙ»

О. Агамалов, докт. техн. наук
Ташлицька гідроакумулююча електростанція,
Южноукраїнськ, Україна, **e-mail:** **olegagamalov@gmail.com**

Запропоновано нову структуру керування для перетворювачів відновлюваних джерел енергії (ВДЕ-П), засновану на виборі режиму їхньої роботи «мережа-ведучий/ведений» в залежності від динамічної жорст-кості (ДЖ) енергосистеми для деякої шини **i** *(контрольної точки) енергосистеми, де можна спостерігати довільне збурення. У запропонованій концепції керування ВДЕ-П у випадку малих значень ДЖ енергосистеми навколо шини* **i** *встановлюється їхній режим керування «ведення мережі», а у випадку великих значень ДЖ енергосистеми навколо шини* **i** *встановлюється їхній режим керування «ведення мережею». Режим роботи ВДЕ-П може змінюватися залежно від вимірюваного значення ДЖ для шини* **i** *енергосистеми.* Бібл. 4, рис. 2.

Ключові слова: відновлювані джерела енергії (ВДЕ), динамічна жорсткість (ДЖ), «мережа-ведучий/ведений» керування (МВВК)

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УПРАВЛЕНИЕ В РЕЖИМЕ «СЕТЬ-ВЕДУЩИЙ/ВЕДОМЫЙ» ПРЕОБРАЗОВАТЕЛЯМИ ВОЗОБНОВЛЯЕМЫХ ИСТОЧНИКОВ ЭНЕРГИИ

О. Агамалов, докт. техн. наук
Ташлыкская гидроаккумулирующая электростанция,
Южноукраинск, Украина, **e-mail:** **olegagamalov@gmail.com**

Предложена новая структура управления для преобразователей возобновляемых источников энергии (ВИЭ-П), основанная на выборе режима их работы «сеть-ведущий/ведомый» в зависимости от динамической жесткости (ДЖ) энергосистемы для некоторой шины **i** *(контрольной точки) энергосистемы, где можно наблюдать произвольное возмущение. В предлагаемой концепции управления ВИЭ-П в случае малых значений ДЖ энергосистемы вокруг шины* **i** *устанавливается их режим управления «ведение сети», а в случае больших значений ДЖ энергосистемы вокруг шины* **i** *устанавливается их режим управления «ведение сетью». Режим работы ВИЭ-П может изменяться в зависимости от измеряемого значения ДЖ для шины* **i** *энергосистемы.* Библ. 4, рис. 2.

Ключевые слова: возобновляемые источники энергии (ВИЭ), динамическая жесткость (ДЖ), «сеть-ведущий/ведомый» управление (СВВУ)

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