New control approach for blackstart capability of full converter wind turbines with direct voltage control

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***Abstract*— This paper presents a new control approach for load pick and restoration of power systems by full converter based wind turbines. In such blackstart scenarios, batteries or other storage devices that can establish frequency or balance generation and consumption of power are not necessarily available. Therefore, a so-called grid forming control scheme is required. The control scheme used in this paper is based on direct voltage control. To balance the generation of power with the load demand, an intermediate circuit voltage control is used. Based on this concept, an alternative speed-power controller is designed to replace the MPPT based speed control in the process of blackstart and restoration. Furthermore, the definition of the frequency in an island grid is discussed. The overall control approach is presented and evaluated based on electromagnetic transient type simulations, involving islanding, load pick up, restoration, and resynchronization.**

***Index Terms*-- power system restoration, islanding, wind energy, frequency control, voltage control**

I. INTRODUCTION

The main problem with network restoration or the operation of island systems is the absorption and distribution of the current load between the various sources located in the system. This is necessary to achieve a balance between generation and consumption. Otherwise, no stationary operation of a power system is possible. In the interconnected network, an imbalance becomes noticeable due to a frequency change associated to the directly grid-connected synchronous generators. This frequency change is globally measurable and is usually compensated first by the primary frequency control. In island networks, there are various approaches to achieve such a balance. In [1-3], doubly-fed induction generator (DFIG) based wind turbines (WTs) are used for the blackstart. The DFIG based wind turbines (WTs) are connected directly to the grid through the stator, like the synchronous generators, hence, they contribute to the inertia of the power system and establish a connection between power deficit or excess resulting in decrease or increase of the system frequency. This information is used as a principle for balancing the generation and consumption by means of the so-called droop control. Theoretically, the power/frequency behavior of synchronous machines can also be emulated. Such a control, called virtual synchronous machine (VSM), is used [4] to control the DFIG. In [5], a direct grid-connected diesel generator is used together with full converter based wind turbines to enable a blackstart of a power system. In this case the frequency gives a direct indication of the active power balance of the system. In grid where an imbalance of consumption and generation does not automatically lead to a corresponding frequency change, single- or multi- concepts can be used [6]. According to these concepts, there are one or more masters with fixed operating points for active power and reactive power. If these operating points deviate, the masters change their frequency and output voltage accordingly. Other sources in the grid can measure these deviations and these are controlled to adjust their injected active and reactive powers. These concepts assume that the masters are controlled like voltage sources, thus, automatically tracking the load changes.

Two alternative grid-forming control methods that can be used to perform the above mentioned tasks are the virtual synchronous machine (VSM) [7], and the direct voltage control (DVC) [8]. On one hand, VSM faces a problem of current limiting and it does not have the capability to fulfil the grid code requirements in Germany [9]. DVC, on the other hand, allows the grid-side inverter of the wind turbine to act similar to a voltage source resulting in covering the load demand automatically as long as it is within the rated power that can be delivered by the wind turbine.

However, using DVC alone does not solve the problem of balancing of generation and consumption of active power. The DVC shifts the problem of balancing generation and consumption into the intermediate circuit of the wind turbine.

In the event of a load pick-up, the DVC adapts the load immediately, which initially leads to an imbalance between the generated power on the machine side converter and the consumed power on the grid side converter. This well-known relationship, which leads to the change of the intermediate circuit voltage, is used in this paper to design an alternative speed/power controller for the wind turbine. The proposed

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speed/power controller replaces the typical maximum power point tracking (MPPT) based speed control in the power system restoration process, since MPPT cannot balance generated and consumed power in an island grid.

Since the load absorption of the wind turbines takes place independent of the frequency by means of the DVC, and the balancing of generated and consumed power takes place on the basis of the intermediate circuit voltage, the frequency has no special significance in this control principle. However, the frequency control should be designed such that the frequency is stabilized in island grid within an acceptable range.

The reminder of this paper presents the proposed control approach for load pick and restoration of power systems by full converter based wind turbines. The control functions of a grid forming wind turbine are firstly presented a discussed. The control of the wind turbine is extended to perform direct voltage control to be able to perfom properly during a blackstart (emphasis on restoration process) of an islanded power system. Besides, it is assumed that no other active network elements with grid forming capabilities exist in the prototype system used in the simulations presented and analyzed in this paper. Furthermore, it is assumed that the necessary wind power for power system restoration is available, and the wind turbine can be started at no or low load up to the maximum available power.

II. Wind Turbine Island Control

A. Direct voltage control

(i)Var-voltage control

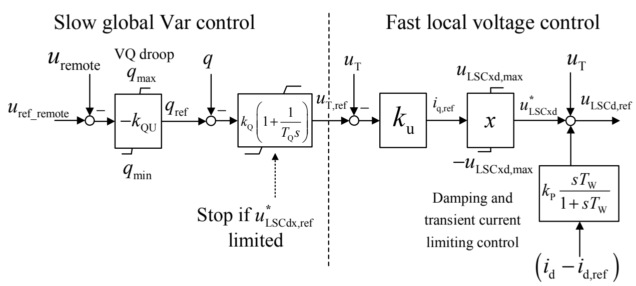

Figure 1. Reactive power control of a WT

Figure 1 shows the reactive power control channel of a WT. The reactive power reference is set on basis of a droop characteristic. This serves as an input to a PI block that determines the voltage reference. The response time of this controller is set 5 - 30 s, large enough to avoid significant control action during network short-circuit and small enough to preclude unnecessary tap movement in on-load tap changing (OLTC) transformers. For events requiring quicker response the downstream direct voltage controller with a proportional characteristic is responsible. A lead-lag block can be added to make the gain dynamically varying. Adding a stabilizing feedback signal, as often done in automatic voltage regulator (AVR) of synchronous generators, is also conceivable. The elimination of the dead-band ensures the continuous voltage control.

(ii)Active power-frequency control

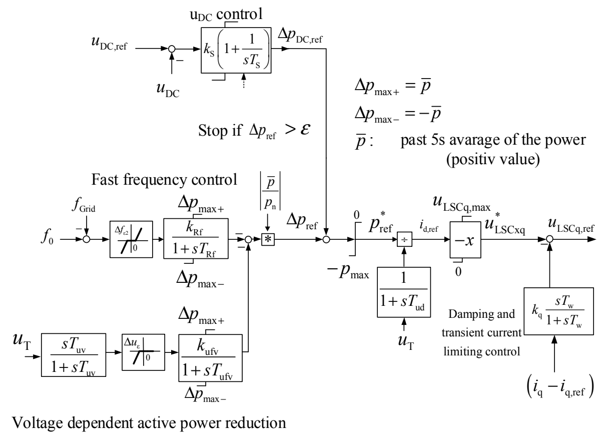

Figure 2. Active power control of a WT

Figure 2 shows the active power control channel of a WT. The output of the DC voltage controller is the active power injected into the network. The active power injection can be calculated as

$$p = u_T i_d = -u_T \frac{u_{Cq}}{x}. \tag{1}$$

Equation (1) describes that the active power can be controlled by using the q-component of the converter voltage. Fig. 2 also shows the frequency control. The frequency control is activated when the frequency exceeds a preset threshold value, e.g. 50.2 Hz in this paper. The gain defines the frequency deviation (e.g. 1.3 Hz) at which the power reduction corresponds with the total power. The time constant is small to tally with the fast response time of converters. One can also define a limitation of rate of change in the delay block.

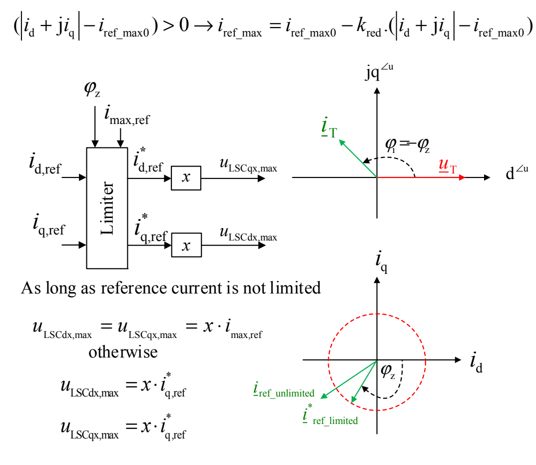

Figure 3. Current limitation of the WT

Fig. 3 shows the current limiting method used in this extended controller. When the actual power electronic converter current exceeds the maximum current of the power electronic converter, a new maximum current value is calculated by using the equation shown on the top of Fig. 3. The new calculated maximum current value is used in the limiter block along with the angle of the grid impedance seen by the power electronic converter. The reference current limits of the d- and q- converter control voltages are limited based on the impedance of the grid and the new calculated maximum current value. This means that the power electronic converter adjusts the reference currents based on the impedance seen by the converter[8].

B. Extended speed and pitch control

In case the generated power by the wind turbine cannot be absorbed, (2) is not balanced, and as a result, the intermediate circuit voltage will rise. Therefore, the intermediate circuit voltage of the wind turbine is a natural indicator for the imbalance of the system. In order to balance (2) in island operation, the incoming power from the machine side converter pMSC needs to be adapted. To find a new active power set point, a PI-controller is used, which adapts the power set point according to the intermediate DC circuit voltage mismatch (cf. Fig. 4). This new control principle is implemented into the wind turbine speed control, marked in red in Fig. 4.

$$\frac{\mathrm{d}u_{\mathrm{DC}}}{\mathrm{d}t} = \frac{1}{c_{\mathrm{DC}} \cdot u_{\mathrm{DC}}}\left(-p_{\mathrm{LSC}} - p_{\mathrm{MSC}} - p_{\mathrm{CH}}\right). \tag{2}$$

In this paper, only one wind speed scenario is simulated. It is assumed that the wind speed is near the rated wind speed of the WT, and there is enough wind power is available to pick up the load. Following this scenario, the startup of the wind turbine will result in nominal speed of the generator (1 p.u). whereas the pitch angle will be maximum to limit the over-speeding of the wind turbine.

III. Test System and Definition of Scenarios

The test system shown in Fig. 4 is modelled and studied as electromagnetic transient (EMT) model in DIgSILENT PowerFactory. The machine side converter and generator of the full converter wind turbine are represented by a current source that is driven by the speed and pitch controller. The DC voltage based speed/power control (Fig. 4 marked in red) is enabled and the classical MPPT based speed control is disabled in this study. The line side converter is modelled as a controlled voltage source with the DVC implemented. The 690 V wind turbine is connected via a 0.69/30 kV transformer to the medium voltage grid, where the load is connected. The medium voltage circuit breaker is switched on to synchronize the WT with the grid.

The test system shown in Fig 4. is used to study the behavior of the new wind turbine control in startup, island, and resynchronization operation. The wind turbine model as well as the parameters of the phase locked loop (PLL) and pitch control are derived from realistic models developed in industry projects, which are not shown in the paper due to confidentiality reasons. Three operational stages, namely startup, island, and resynchronization, are studied in one simulation run.

(i) $t < 5$ s - Start-up mode (island operation)

The wind turbine is under no load condition, initialized with a fixed PLL frequency. The only reason for the fixed frequency is to generate nominal conditions before the load pick-up occurs. While studying load pick-up, the fixed frequency PLL is switched to standard PLL so that the frequency dynamics can be observed and power/frequency control can be done. Since no load condition is an island condition, this is the starting point of the new intermediate circuit voltage based speed/power control. Therefore, the MPPT based speed control is disabled and the classical DC voltage controller is on the line side converter (LSC). This is done because the DC voltage is now controlled by the new speed control. The LSC is controlled through the DVC [8].

(ii) 5 s < t < 35 s - Load pick-up (island operation)

In this time period, the control is the same as under start-up mode, except for the PLL, which is now without a fixed frequency output. At time t = 5 s, the pick-up of an active power load of 0.85 p.u. from the nominal wind turbine power together with the corresponding increase in reactive power takes place.

(iii) $t > 35$ s - Resynchronization (grid operation)

At time t = 35 s, the resynchronization of the wind turbine with the medium voltage place. The goal is to check how the control deals with grid connection. After the synchronization, the MPPT and the DC link voltage controller on the LSC side are activated, whereas the DC link voltage control in the modified speed control is deactivated.

IV. Simulation Results

Fig. 5-6 and Fig. 8-12 show the dynamics of voltage, active and reactive power, DC link voltage, frequency measured by the PLL, pitch angle, wind turbine speed, and mechanical torque.

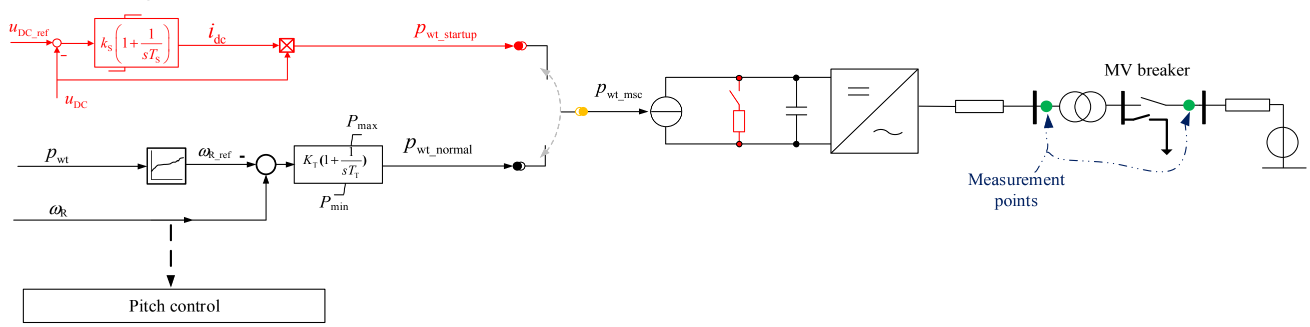

Figure 4. Test system

A. Power/ frequency dynamcis

Fig. 5 and Fig. 6 show the dynamics of the frequency and active power supplied by the WT to balance the load, respectively. As it can be seen from both figures, even though the load is already balanced, the frequency keeps decreasing. In other words, the load-generation of active power is already balanced but the frequency does not show the correspondence to this balance of power. From this, it can be concluded that there is no relationship between frequency and power in an island grid. This is reasonable, since the load is passive and rotating masses do not exist.

This means that the frequency is not an indicator of active power balance in an island grid. Based on the parameters of the PLL, the frequency could settle at any value, provided that the system load demand will be met. In order to explain this phenomenon in detail, a simplified inverter control with a simplified PLL is shown in Fig 7. It can be seen from the structure of the PLL that it follows the frequency of an external source, hence it cannot establish its own frequency. The PLL tries to minimize the error between the internally generated angle of voltage δ_{est} and the measured angle of the voltage δ_m of an external source. In the absence of an external source, the PLL can settle at any frequency value based on how it is tuned, provided the load-generation of active power is balanced. In such scenario, the external feedback loop is needed to stabilize the frequency within the acceptable range.

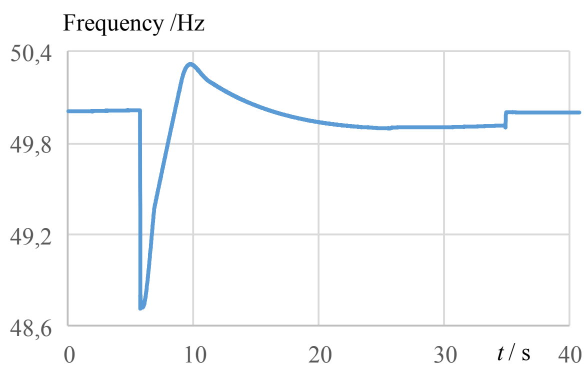

Figure 5. Frequency measured by the PLL

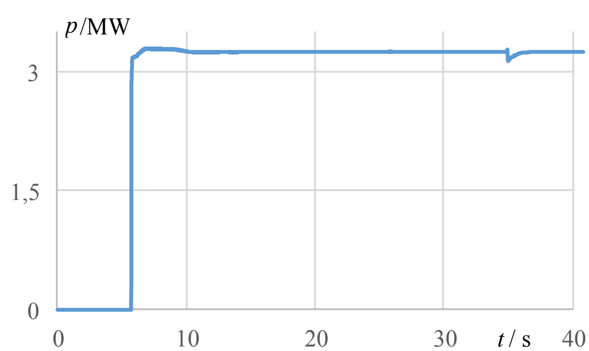

Figure 6. Active output power wind turbine

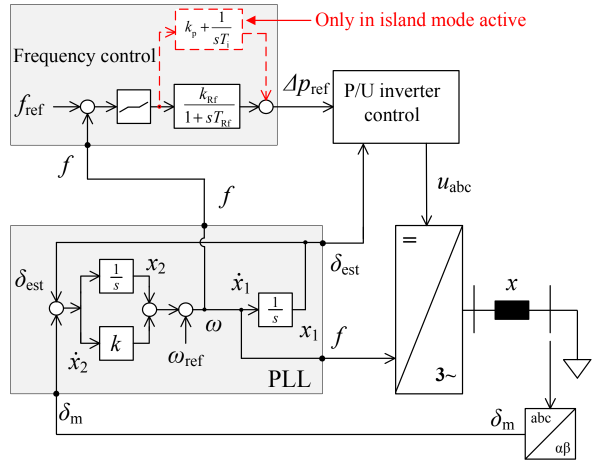

Figure 7. Simplified inverter control with PLL

The Δp_{ref} (cf. Fig. 7) influences the q- component of the converter reference voltage $u_{LSCq,ref}$, thus influencing the converter angle, which modifies the grid frequency. This change, therefore, goes also directly into the measured angle δ_m of the PLL. Thus, this corrective action stabilizes the frequency at a certain value. In order to bring back the frequency back to 50 Hz, a PI based control, as shown in red in Fig. 7, is necessary in this feedback loop. This can be activated during the island mode and deactivated during the grid connected mode. It is however important to note that the change in the frequency has no effect on the supplied power as the load generation balance has already been met.

The dead band in the frequency loop is set around 200 mHz, so that the control doesn't interfere with the normal operation of the power system in the grid connected mode. The use of the PI based control in the frequency loop in the grid connected mode is not recommended as the integrator will drive the power set point as long as the error in the frequency remains. This can be problematic since this action will either deplete the DC link voltage or force it to rise to a value where chopper will have to act to limit it. This feedback loop of the frequency could also be directly implemented into the PLL as a feedback of the estimated angle. However, there exists a relationship between power and frequency in grid connected operation and therefore, a true frequency/power control is needed. Due to this reason the frequency stabilization / control is placed outside of the PLL.

Fig 8-9 shows the voltage and the reactive power supplied by the wind turbine respectively. The voltage can be set higher in the island mode because the voltage will fall during the load pickup as can be seen in Fig 8.

B. Speed control dynamics

Fig. 10-12 shows the dynamics of the wind turbine speed and DC voltage control. The wind turbine, initialized with no load, has a high pitch angle to limit the over-speeding of the WT. It keeps the WT at nominal speed in the first two seconds before an active power load with 0.85 p.u. of the nominal power is picked up. The sudden load increase results in a reduction of the intermediate circuit voltage (cf. Fig. 12) compensated by the modified speed/power controller. The new speed control reacts to this by increasing the electrical power taken from the generator terminals and therefore, increasing the electrical torque (cf. Fig. 10). As a result, the mechanical speed (cf. Fig. 11) decreases since the pitch control is not fast enough to keep up with the sudden load pick-up. However, the kinetic energy of the wind turbine as well as the energy stored in the intermediate circuit capacitor still help to cover the time delay, before the pitch control kicks in. As a result, the active power can be kept constant by the wind turbine control (cf. Fig. 6). At some point in time, the mechanical torque becomes bigger than the electrical torque and the sign of the acceleration changes and the wind turbine accelerates again (cf. Fig. 11). In steady-state, it can be seen that this must have happened at around 3.8 ° pitch angle. In the end, the pitch control brings the speed back to 1 p.u. It is important to note that wind turbines can pick-up loads in the range of their nominal power without reaching inadmissible system states.

V. Conclusion

This paper introduces wind turbine control principle based on the direct voltage control (DVC), which adapts to the load almost immediately, without resorting to measurement of system frequency. Therefore, unlike current practices, there is no primary frequency control scheme needed to support the active power balance of load and generation in island operation of an electrical area. In addition, it is shown in this paper that there is no relationship between active power and frequency in this island operation without machines with rotating masses. Therefore, it is proposed to use the intermediate circuit voltage as an indicator of the active power balance of generation and consumption, since there is a distinct relationship between incoming (generated) power and outgoing (load) power in the intermediate circuit that results in changing voltages in case of active power imbalance. Numerical simulations show that the electrical torque can be controlled according to the intermediate circuit voltage, and, then, the pitch control stabilizes the wind turbine by adapting the mechanical torque according to the mechanical speed, resulting in a stationary operating point. The frequency, since it has no relationship with the load in island operation, is kept within the dead bands specified in the frequency control and has no influence on the control at all.

The proposed control strategy can work in islanded grids, like microgrids and in big power systems. Only island operation needs to be detected (which has not been the focus of this paper) and the speed/power control can then be switched between MPPT based or intermediate circuit voltage based control. The rest of the control does not need to be changed. Another advantage is that this control does not need communication infrastructure.

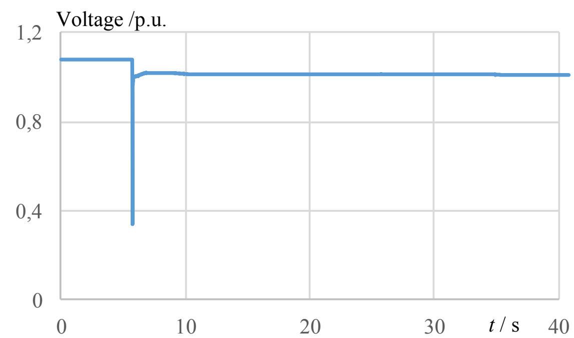

Figure 8. Voltage magnitude of wind turbine reactor output

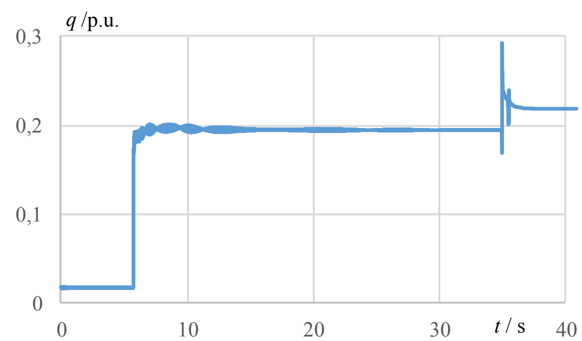

Figure 9. Reactive output power of wind turbine

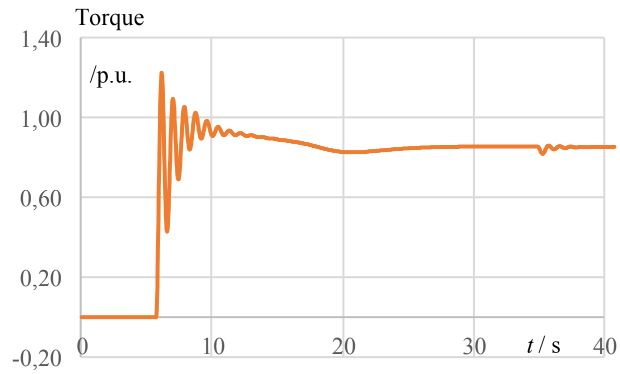

Figure 10. Wind turbine torque

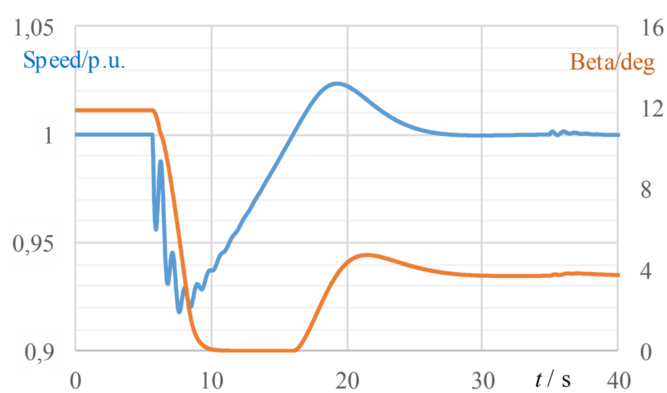

Figure 11. Speed and pitch angle of wind turbine

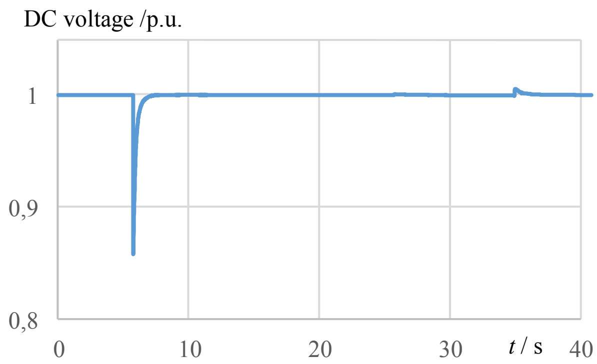

Figure 12. Intermediate circuit voltage

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