Short-Circuit Contributions of Full-Converter Wind Turbines

R. J. Nelson, *Member, IEEE* and H. Ma, *Member, IEEE*

***Abstract*—Full converter wind turbines respond somewhat differently than directly-connected machines to short circuit conditions. In distinction with directly-connected machines, full-converter wind turbines have a controlled response to system short circuits. Consequently, they do not behave quite like a voltage behind a reactance, as conventional synchronous or asynchronous machines do. Also, they do not have negative or zero sequence impedances in the same sense as machines. Correct modeling of these wind turbines may require some modification of existing short circuit programs, which are based on the characteristics of synchronous machines.**

***Index Terms*—fault, fault current, type 4 wind turbine, balanced fault, unbalanced fault, full converter**

I. BACKGROUND

Short circuit contributions from wind farm are a major concerning for protection engineers [1-4]. The short circuit behavior of a generator is normally understood to describe the uncontrolled current output of a synchronous generator following a fault. It is normally delineated by 3 time periods – the subtransient, which encompasses the first few cycles after fault inception, the transient, encompassing the time period after the first few cycles, but before the transition into a steady-state short circuit current, and, finally a steady-state (continuous) value. In full-converter wind turbines, where the machine is isolated from the system by a full AC-DC-AC converter, these three time delineations do not exist. There is a transient overcurrent, immediately following the fault inception, but it is followed by a very rapid transition into the steady-state condition, which is actually a programmed response of the converter. Consequently, there is no reason to distinguish between a "subtransient" response and a transient response. Unlike synchronous machines, which have a characteristic negative and zero sequence representation, the zero- and negative sequence response of converters is a design parameter and there is no corresponding sequence representation. This paper describes some of the characteristics of full-converter wind turbines and their simulation in a short circuit program. This paper draws heavily on work reported previously by other Siemens engineers.

II. INTRODUCTION

THIS paper describes the practices adopted by a major wind turbine manufacturer of full-converter wind turbines. Although the practices may differ, in some respects, from those of other manufacturers, it is believed that the characteristics described in this paper apply to full-converter wind turbines in general and that the assumption, commonly applied by system protection engineers, that these turbines can be replaced with an equivalent synchronous machine, are impractical.

The balanced short circuit contribution from type 3 double fed induction generator (DFIG) is investigated and reported in [5-6]. The full-converter wind turbine, sometimes called a type 4 or variable-speed, full converter (VS-FC) wind turbine generator interfaces the power system with a full AC-DC-AC converter, normally comprised of two ac-to-dc converters with an intermediate dc bus. See Fig 1. The interface between the grid and the wind turbine is the DC-AC converter. The fault on grid side has a similar effect on full converter wind turbine as common voltage source converter (VSC). The response and control of VSC to an unbalanced fault are published in [7-9].

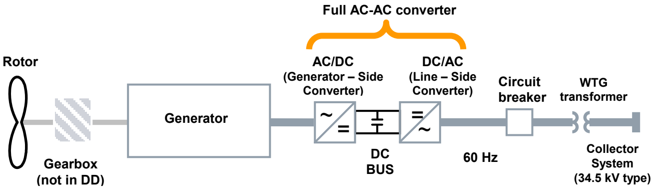

Fig 1 Variable-Speed Full-Converter (VS-FC), or Type 4, WTG

The generator may be an asynchronous or synchronous (e.g. permanent magnet) machine in the geared configuration and is normally a synchronous machine (permanent magnet or separately-excited) in the direct drive (DD) configuration, which does not have a gear box. Active power from the WTG rotor is provided to the generator, which, in turn, provides electric power to the generator-side converter. The generator-side converter may provide magnetizing current to the generator, as required. The generator-side converter converts the real power to dc and the line-side converter provides active power and voltage support to the system at system frequency. Note that there is no relationship between the frequency of the generator and the system frequency. The generator frequency is normally optimized to maximize mechanical energy extraction from the wind, normally

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corresponding to a low frequency at low wind speeds. Conversion of the generator real power to dc eliminates the necessity to tie the generator frequency to the system frequency. Power from the dc bus is provided at system frequency by the line-side converter, which generates a system-frequency wave form in synchronism with the system, using a phase-locked loop control.

It may seem that a full-converter would have many similarities to a synchronous generator, with its typical "voltage behind a reactance model" and voltage and current wave magnitudes and phase angles based on the system voltage. But the operation of the converter controls limits outputs during low-voltage conditions to much lower levels than would be expected in a synchronous generator of similar capacity. The converter controls can vary significantly from one design to another (even two designs by the same manufacturer), depending on the characteristics of the specific devices used in the converter and the amount of design margin used by the manufacturer.

Normally, the initial transient (typically of duration ½ cycle) is limited to a current of 2.5 pu or less, after which the controls limit the current to a predetermined value. The value of the initial transient can be expected to vary from one converter design to another and should be obtained from the manufacturer, if this is considered a parameter of interest. Siemens uses a "Fault Ride-Through" logic, which limits the short circuit current to a value between 1.1 and 1.2 pu after the initial transient.

For positive sequence voltages below the FRT initiation voltage, reactive current receives priority over active current in Siemens turbines at a rate of 2% reactive current for every one percent that the positive sequence voltage drops below the nominal voltage of 1 pu. Typically, the FRT initiation voltage is set at 90%, so a fault that results in a positive sequence voltage of 50%, for example, would result in an output reactive current of 100%. Positive sequence voltages below 50% result in only slight increases in reactive current, limited to the aforementioned 1.1 to 1.2 pu range. Positive sequence fault voltages between 50% and 90% may result in some active power output by the wind turbine because the active and reactive currents are in quadrature. For example, if a wind turbine with a rated capacity of 2.3 MW is putting out 1.5 MW (0.65 pu) and a fault occurs, resulting in a positive sequence voltage of 0.80 pu, the wind turbine would be expected to continue outputting 1.5 MW, since the sum of the required reactive current ((1pu.-0.8pu.)*2=0.4 pu) and real current (0.65/0.80 = 0.81 pu) is less than the capability of the machine (i.e., ($\sqrt{}(0.4^2 + 0.81^2)$ = 0.90 pu) based on the MW rating of the wind turbine. Although the fault contributions of this type of converter are relatively small compared to those of a synchronous or induction generator, which can exceed 5 pu subtransiently, they differ significantly from those of a synchronous machine because they have no direct inverse relationship with the fault voltage or with the impedance between the wind turbine and the fault. Consequently, type 4 WTGs cannot be properly modeled, even for a simple 3-phase balanced fault, by synchronous generator parameters.

The situation for unbalanced faults is even more complex. For balanced three-phase faults, the currents are a balanced positive sequence set. For unbalanced faults, again the currents are a balanced three-phase set that satisfy the criterion that the sum of the currents leaving the machine at all times is zero (i.e., that ($i_a + i_b + i_c$) = 0) so that the dc bus can retain its charge during the fault. The fault currents (after the brief transient) are equal in magnitude and 120 degrees out of phase with each other. This is totally dissimilar from the performance of a synchronous or induction machine during an unbalanced fault. For a machine, the phase currents are generally unequal and can be calculated by the method of symmetrical components. For a full-converter, the output of the converter during a fault is determined by the positive sequence voltage at the turbine terminals (which determines the reactive component of current required), by the necessity to maintain a charge on the dc bus without excessive ripple, and by the operation of the proprietary converter controls.

III. SIEMENS' TESTING AND SIMULATION – BALANCED

A peculiarity of the full-converter design is that the short circuit performance is determined entirely by the performance of the line-side converter. The mechanical system, generator, and generator-side converter have little or no influence on the current magnitude or phase, since their principal functions are to move to a safe state during the short-circuit condition and to continue active power production, to the extent permitted by the fault conditions. The components remain active but do not contribute short circuit current.

Testing of the short circuit and fault ride-through capability of the Siemens wind turbines was performed and verified at a network in Hovsore, Denmark. The schematic of the test circuit appears below in Fig 2:

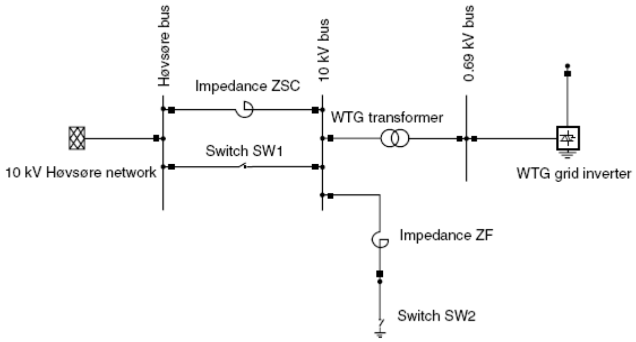

Fig 2 Hovsore test network

Details of the tests and simulations are described in considerable detail in [10]. A short summary, with figures extracted from [10] follows.

A balanced three-phase solid (V=0%) fault was applied on the 10kV bus. In the below figures are shown a comparison between measurements and simulations performed with a simulation program (DigSilent) commonly used in Europe.

Although the fault voltage is zero, the voltage at the WTG terminals (Fig 3) remains above zero because of the transformer impedance. Since the voltage drops below 50%, active current drops to zero reactive current exceeds 100% (Fig 4) for the duration of the fault. During the fault, phase currents in all three phases are identical and of the same magnitude as the reactive current. After fault clearing, active and reactive currents go back to pre-fault levels. There is some oscillatory current following the fault but the oscillations are positively damped and are minor after a few seconds.

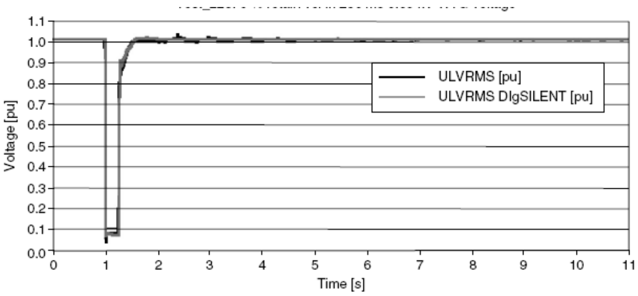

Fig 3 WTG terminal voltage

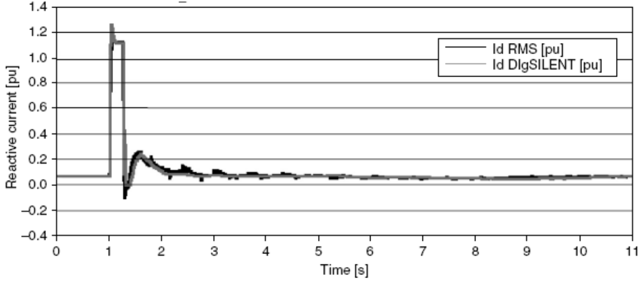

Fig 4 Reactive current of WTG

The simulation was able to capture the electrical performance of the line-side converter very accurately. Similar simulations have been made using PSS/E, with similar results.

An interesting characteristic of the balanced short circuit behavior is that the short circuit current does not significantly exceed full load current. Also, it does not change significantly with decreasing terminal voltage during the fault below a terminal voltage of roughly 40% to 50% of nominal, below which the reactive current does not increase.

IV. Siemens’ Testing and Simulation – unbalanced

Corresponding results are described in [10] for a line-line fault between phases B and C on the 10kV network, which appears to be a line-neutral fault on phase B at the LV terminals because of the delta-wye configuration of the WTG transformer. Again, these results are summarized in figures 5 to 16, extracted from [10], as follows.

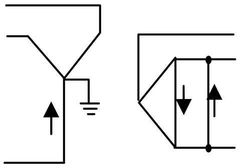

Fig 5 Fault current transformation

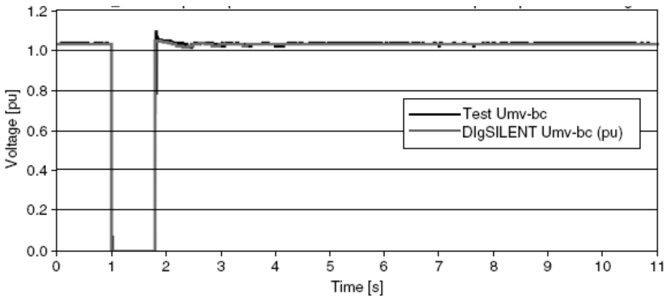

Fig 6 Magnitude of Voltage B-C on 10kV network

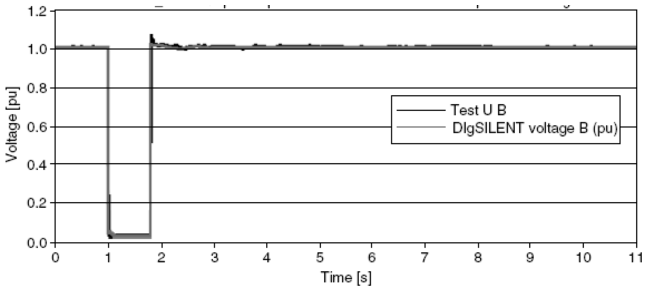

Fig 7 Voltage phase B at WTG terminals

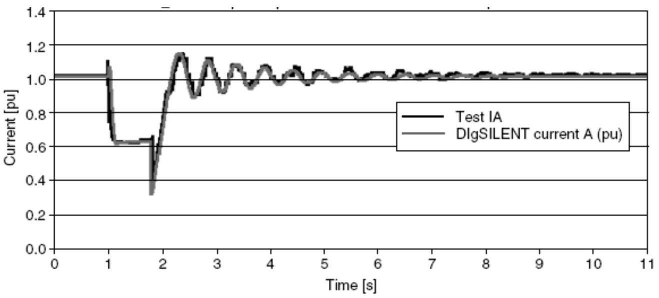

Fig 8 Phase current, phase A, at WTG terminals

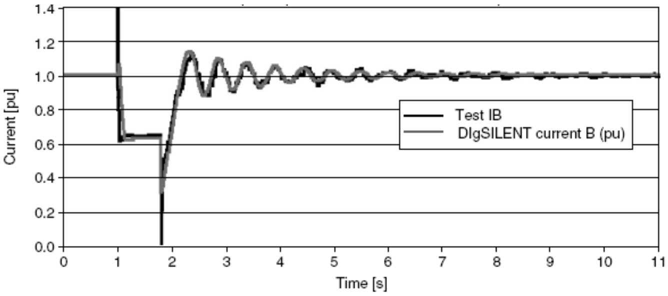

Fig 9 Phase current, phase B, at WTG terminals

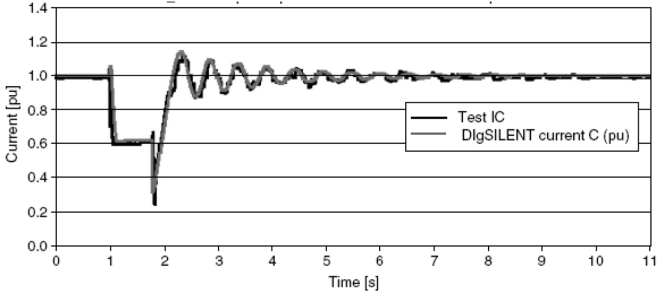

Fig 10 Phase current, phase C, at WTG terminals

The 10kV solid line-line fault in phases B-C of the 10kV network (Fig 6) appears to the turbine to be a line-neutral fault on phase B of the WTG (Fig 7) because of the phase shift in the wye-delta step-up transformer (grounded wye at the turbine, delta on the 10kV side). (Fig 5) Phase to neutral voltages for phases A and C at the turbine (not shown) had only a minor reduction in magnitude. After a brief transient immediately after fault initiation and fault recovery, most pronounced in the faulted phase (Figure 9), where the fault current goes to roughly 1.4 pu transiently, phase currents in all 3 phases are the same throughout the fault (Figs 8-10).

Inasmuch as two phases are taken out of service in the network, real power cannot be delivered on these phases, so real power output drops by about 2/3 to about 1/3 of the pre-fault level, delivered roughly equally by the two unfaulted turbine phases. Positive sequence voltage is about 2/3 of nominal, and fault current is only about 2/3 of rated current (Figures 7-9).

As with balanced faults, the short circuit current is relatively easy to calculate and simulate, but the performance is distinctly dissimilar to that of synchronous or asynchronous machines commonly assumed in short circuit analysis programs. Although it may be possible to roughly estimate maximum short circuit currents for type 4 machines by using a synchronous generator equivalent, this is an inaccurate representation. Such estimates tend to overstate the actual currents observed during short circuits.

A peculiarity of this type of machine is that the unbalanced fault current may well increase as the turbine positive sequence voltage during the fault increases, depending on the level of active power production. Additionally, the short circuit current for an unbalanced fault can generally be assumed to be less then for a balanced fault and is typically well under 1 pu.

V. SUMMARY AND RECOMMENDATIONS

The Siemens type 4 (VS-FC) wind turbine generator design provides relatively low fault currents after an initial transient, that are quite predictable and relatively easy to estimate, but which are not compatible with the capabilities of existing short circuit calculation programs, which assume the use of synchronous generators. This paper shows that, although some parameters may be functions of specific control designs, the short circuit currents of these WTGs is relatively easily to calculate and can be simulated by commercially available simulation programs. The two principal requirements for proper modeling of the short-circuit response of Siemens type 4 machines after the initial transients are that the instantaneous sum of the currents must equal 0 and that the lagging reactive current increases by 2% for every 1% drop in positive sequence voltage below 100% after initiation of FRT, which is typically at 90% of nominal voltage. It seems appropriate that vendors of short circuit calculation programs should make allowances for the use of full-converter equipment in power system software.

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