# Improving the efficiency of a wind turbine using Thyristor Switched Series Capacitors- A simulation study

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*Abstract:* - The paper describes the operation of a Thyristor Switched Series Capacitors (TSSC) circuit for wind turbines. The TSSC circuit belongs to the Controlled Series Capacitor (CSC) circuits that have been used in power transmission lines to improve the power factor. But to improve the efficiency of a wind turbine and make it more fault-tolerant is to avoid gearboxes and use direct-drive systems that employ variable speed electric generators and solid-state electronic converters. The downside is that systems like the above suffer from high inductive reactance, therefore, there is the need to counteract for any reactive losses, to improve the power factor as well as the efficiency [1]. This paper describes the benefits and drawbacks of applying the TSSC to a typical wind turbine by PSPICE simulation and suggests a new topology called Thyristor Switched Parallel Capacitors (TSPC). The near future implementation will be hosted in an FPGA.

*Key-words:* TSSC, wind turbine, HAWT, TSPC, PF.

## 1 Introduction
Our civilisation's economy was based into the conventional energy sources such as oil, coal, and natural gas but that have been proven to be extremely destructive and very harmful to the environment and to human health, therefore, the Kyoto Protocol for greenhouse gas reduction was entered into force in 2005.

In order to reduce greenhouse gases and to reach the target of the anthropogenic emissions of $CO_2$ that was set by the Kyoto Protocol, conventional fuels should be replaced by Renewable Energy Sources. In recent years significant effort has been given to wind power which every year is increasing at over 20%, with a worldwide installed capacity of 539,581 MW, at the end of 2017. Today, more than 83 countries around the world use wind power on a commercial basis [2].

Wind turbines are now considered to be a mature type of technology and nowadays are available commercially in a wide range of capacities, up to 12MW from General Electric. This is the world's most powerful wind turbine to date [14]. Figure 1 shows the way that the wind turbine diameter and power have increased in the last 40 years. The theoretical maximum aerodynamic conversion efficiency of wind turbines, from wind to mechanical power, is 59%.

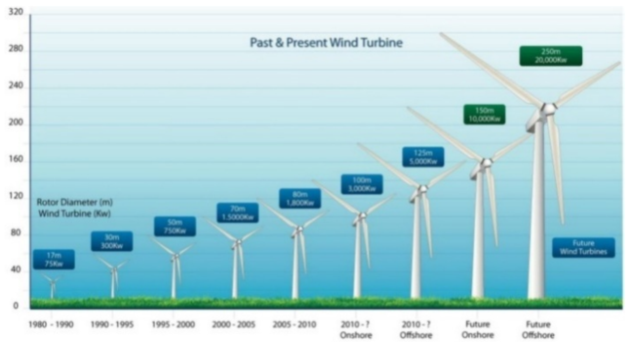


**Fig. 1** Wind's turbine rotor diameter and power from 1980 [2].

In practice, in low or high winds the wind turbines have to be shut down therefore, the average year-round efficiency of most turbines is about half. Furthermore, a reduction of the average efficiency is caused by mechanical losses from generator and due to the fact that the machine does not always operate in its optimum working point [3].

## 2 Wind Turbines
There are two main types of wind turbines, which are the horizontal axis wind turbines (HAWTs) and the vertical axis wind turbines (VAWTs) [3].

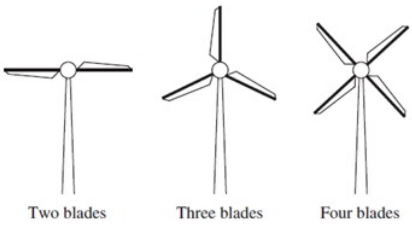


**Fig. 2** Main types of Horizontal axis wind turbines [3]

Nowadays the basic system of HAWT consists of a large rotor containing two, three or four blades, as shown in Figure 2. These blades are mounted on a horizontal shaft at the top of a tower. The design with the two-bladed machine has the lowest cost. However, the main drawback is the high level of generated noise.

Four-blade machines, even though they have the advantage of a good rotor balance, are heavier and less cost-effective. Today the majority of the turbines are been constructed with three blades, which is the type of HAWT that offers smoother rotational operation, lower noise and not very high cost.

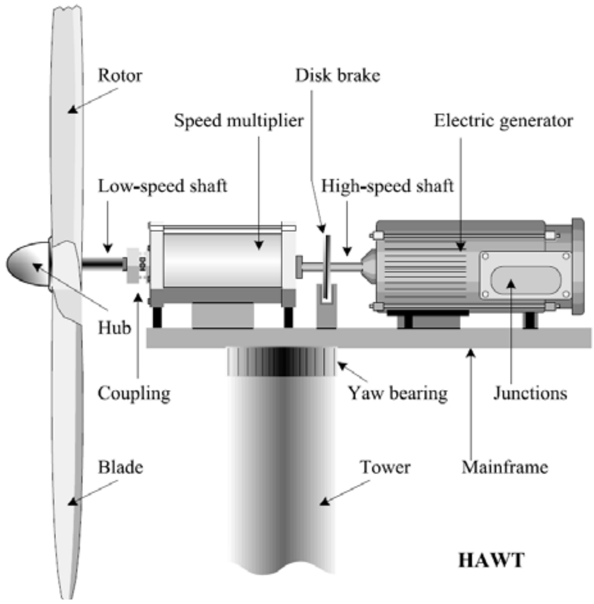


**Fig. 3** Schematic diagram of equipment contained in a nacelle of a HAWT [4]

Figure 3 shows a nacelle, which is the equipment found on the weather compartment at the top of a tower of an HAWT. A gearbox is normally used to increase the slow rotation of the shaft of an HAWT which is connected to the generator. A braking system as shown above connects the gearbox and generator which are attached directly to the turbine shaft. The produced electricity from the generator is taken via cables through the tower to a substation and eventually to the grid [3].

The usual rotation speed of modern wind turbines varies between 5 and 20 rpm while generators operate between 800 and 3000 rpm. Consequently, it is necessary a speed-up gearbox to be used in order to increase the speed to the required level [3]. However, the gearboxes are the most likely component that can cause problems or even failures, therefore, they require frequent maintenance. Hence, in order to overcome this drawback, direct-drive systems have been developed. In these systems the rotor is connected directly to the generator.

## 3 Types of Wind Turbine's Gearboxes

There are several types of gearboxes that can be used in wind turbines, with the most common to be the conventional, the magnetic, the CVT and the torque splitting.

**Torque Splitting -** For solving some of the above-mentioned gearbox problems, on 2.5 MW plus size wind turbines, the torques splitting technique was used. This system in order to split the torque from the rotor blades evenly, among the existing four generators (operated in parallel), uses a multiple-path gearbox design.

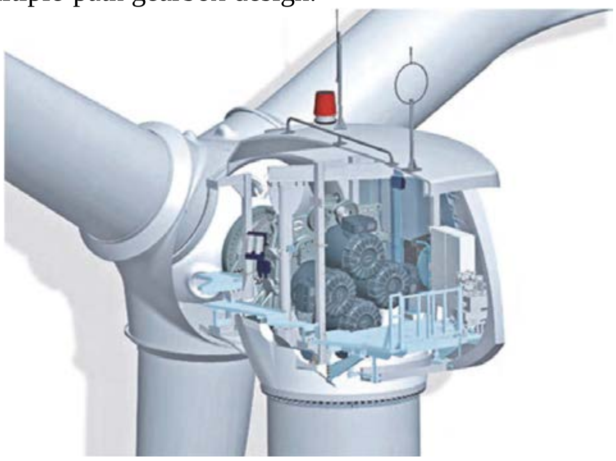

**Fig. 4** Torque splitting between four electrical generators on the 2.5 MW Clipper Liberty [4].

Furthermore, if there is a fault in one of the generators or gear sets, the wind's turbine production capacity is only reduced by 25% until the problem can be fixed [4].

**Continuously Variable Transmissions (CVTs) -** Transmissions of the CVT type can vary continuously through an infinite number of gearing ratios, compared to the standard gearbox, which varies between a set number of specific gear ratios [4].

**Magnetic bearings -** A possible solution to the shaft misalignment problem is the usage of magnetic bearings. The benefits of magnetic bearings include durability, smaller frictional losses and increased reliability at a reduced weight.

The maintenance of all the above type of gearbox as well as the conventional gearbox of a wind turbine is very expensive to manufacture and to replace it in case of failure. In order to extend the life-span of a gearbox, regular maintenance is needed, which adds to the overall cost. Therefore, gearbox reduces the efficiency of a wind turbine due to inertia; it is vulnerable to wind gusts and the most likely part of a wind turbine to fail.

One way to improve the efficiency of a wind turbine and make it more fault-tolerant is to avoid using gearboxes and use **direct-drive systems** instead. At gearless or direct-drive wind turbines, the rotor is the only moving part that transfers the energy from the blades to the electric generator via a low speed shaft. Those wind turbines eliminate gearboxes by replacing them with variable speed electric generators and solid-state electronic converters.

Overall, it can be said that the advantages of the direct-drive mechanism for wind turbines, are the increased efficiency, as the power is not wasted in friction, the reduced noise, as it is a simpler device and finally, the high torque at low rpm [4].

Direct-drive wind turbine should not be direct connected to the electrical grid, due to the variation of the frequency, caused by wind gusts at the rotor blades. In order to solve the above mentioned problem, a DC link and inverter converts the produced energy to parameters which are suitable for transmission to the electrical grid.

## 4 Operation with An Uncontrolled Single-Phase Diode Bridge Rectifier

The specifications of the national grid require a fixed voltage and fixed frequency. However, due to wind's speed variations, the output voltage and the frequency of the wind's turbine electric generator varies too. Therefore, the variable AC signal from the wind turbine electric generator has to be converted to DC signal, with the use of a rectifier. The rectified DC signal can then be converted back to AC at a fixed amplitude and frequency. An arrangement that would allow this to take place is shown in Fig. 5.

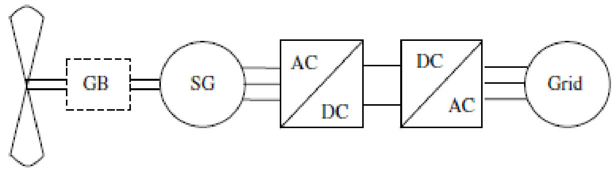


**Fig. 5** Wind turbine with synchronous generator [5].

Figure 5 shows a wind turbine's rotor on the left-hand side. Next and to the right they can be seen the main shaft, gearbox (GB), generator (SG), rectifier (AC/DC), DC link, inverter (DC/AC), and grid [15]. Depending on the condition, the inverter could be either a diode rectifier or a controlled rectifier. Similarly, the inverter might either be a PWM inverter or an SCR inverter [5].

In stand-alone systems, in order to minimize the cost a simple and low-cost converter is preferred. The simplest possible rectifier circuit that most commonly is used in converting AC power to DC, is the standard single-phase diode bridge rectifier. The output voltage in this rectifier is not fix and it depends exclusively on the amplitude of the input voltage. This is due to the lack of any voltage feedback control loop in the rectifier. Figure 6 shows a schematic diagram of the standard single-phase diode bridge rectifier circuit.

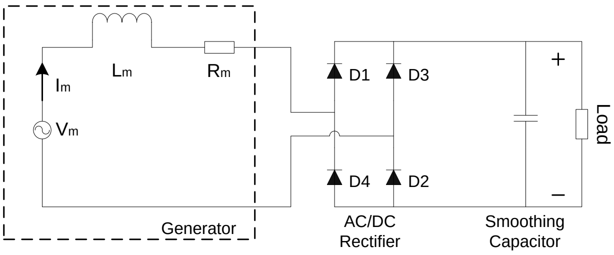


**Fig. 6** Standard single-phase rectifier circuit

A single-phase full wave rectifier converts the given AC input voltage to DC voltage at the output. During the positive half cycle of the back-EMF voltage waveform, only diodes D1 and D2 conduct. On the other hand, during the negative half cycle only diodes D3 and D4 conduct.

However, due to the generator's inductance, current cannot instantly be transferred from diodes D1 and D2 to diodes D3 and D4. Therefore, there will be a period of overlap when current in D1 and D2 is falling and current in D3 and D4 is rising. This will result, as Figure 7 shows, in a phase shift between the back EMF voltage (Vm) and the first harmonic of the generator AC current (Im1).

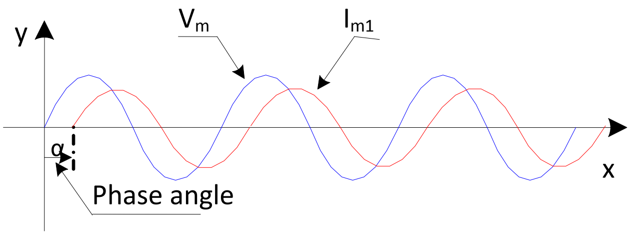


**Fig. 7** Generator back EMF Vm and the fundamental current waveform (Im1) showing the effects of overlap [6].

As a result of this phase shift, the power that should be transferred from the generator to the load suffers from losses.

The generator power output P, if it is assumed to have a purely sinusoidal back emf voltage, is given by Eq. 1:

$$P = V_m I_{m1} \cos a \qquad (1)$$

where α is the phase angle between Vm and Im1. If the angle α is minimised, then the power delivered to the load will be clearly increased. This can be achieved if a Series Resonant Circuit (series RLC) is used. In a series-resonant RLC circuit the inductive reactance is equal in value to the capacitive reactance. In other words, $X_L = X_C$. The point that this occurs is called the circuit's Resonant Frequency point, ($fr$). In case a series RLC circuit is analysed this resonance frequency produces a Series Resonance [6].

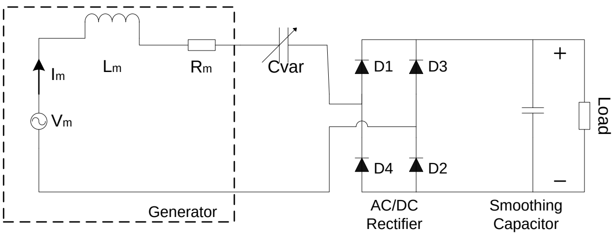


**Fig. 8** Generator with variable capacitor [6]

In order to achieve that a variable capacitor for high voltage and high current is needed, but such a variable capacitor is not commercially available.

## 5 Thyristor Switched Series Capacitor Rectifier (TSSC)

Figure 9 below, shows a TSSC circuit which consists of a number of capacitors in series. Each capacitor is shunted by a switch composed of two anti-parallel thyristors [7, 16]. All capacitors are of the same value $C_{TSSC}$.

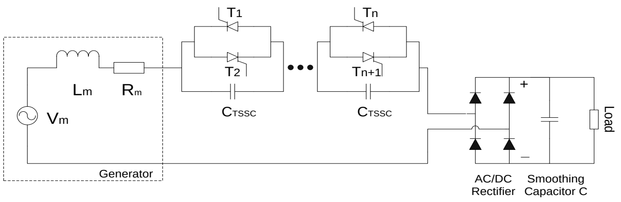


**Fig. 9** TSSC main circuit [8]

In order to control the overall capacitance, it is necessary to conduct or block each of the thyristor pairs. The capacitor $C_{TSSC}$ is short circuited when a thyristor pair conducts. In case that a thyristor pair is open, the value $C_{TSSC}$ is added to the total capacitance $C_T$. The total capacitance of the circuit is given by Eq. 2:

$$C_T = C_{TSSC} / m \qquad (2)$$

where m is the number of active capacitors. When all capacitors are bypassed then the equivalent capacitance becomes $C_T = 0$ F. To increase the output power it is necessary to correct the power factor. Therefore, the capacitance of the system $X_C$ should be equal to inductance $X_L$ as shown in Equation 3:

$$X_C = X_L \Rightarrow \frac{1}{\omega C_T} = \omega L \Rightarrow C_T = \frac{1}{\omega^2 L} \qquad (3)$$

All the thyristors are commutated "naturally" and therefore they turn off when the current crosses zero. At that moment, as Figure 10 shows, a capacitor could be inserted into the line, right at the zero crossings of the line current.

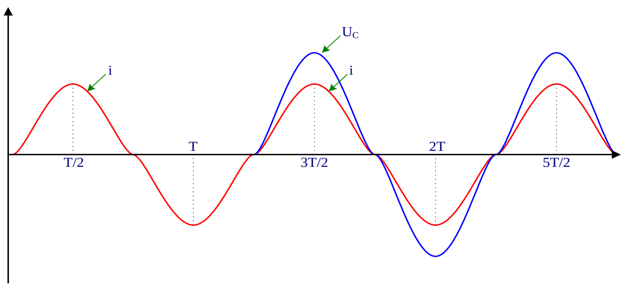


**Fig. 10** Capacitor insertion at zero current voltage [8]

Once the capacitor is in line, it will be charged to its maximum, during the full half-cycle of the line current. Then the capacitor will be discharged from its maximum to zero during the negative line current cycle [9, 10].

For our simulation model a PMSG with 4poles have been used, although PMSG with much higher number of poles have been reported [11, 12]. The frequency at the generators with high number of pole pairs is much closer to the desired 50Hz electric grid frequency compared to PMSG with low number of pole pairs, but the inductive reactance is increased. This is because the inductive reactance is proportional to the frequency as shown in Eq. 4:

$$X_L = L\omega = L 2\pi f \qquad (4)$$

The circuit shown in Figure 9 has been simulated for electrical frequencies between 0.4Hz and 1.333Hz. In order to correct the power factor a maximum of 1627 capacitors have been used. Each capacitor has a capacitance of 358mF. This number of capacitors at so high capacitance is for simulation purposes only, as in practice these numbers are not feasible. The conclusion is that a large number of capacitors in total are needed. To simplify the simulation a maximum number of 1627 capacitors was used.

Table 1 shows the number of active capacitors for various speeds of PMSG.

| ω (rpm) | m |
|---|---|
| 6 | 1 |
| 8 | 21 |

| | |
|---|---|
| 10 | 35 |
| 12 | 188 |
| 14 | 369 |
| 16 | 651 |
| 18 | 1053 |
| 20 | 1627 |

The simulation was carried out in PSPICE. The switching devices have been simulated by using the “W1890/-55C” model in PSPICE with an internal resistance of 1 Ohm. For the diodes, the model “BYT30P-600” was used.

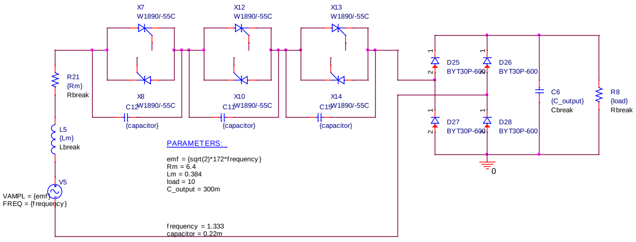


**Fig. 11** TSSC pspice model

Simulation has been carried out and the results for the phase current, the output voltage and the output power are shown at the Table 2 below.

Table 2 shows the simulation results

| ω (rpm) | Electric Freq. (Hz) | DC voltage (V) | Output Power (W) with TSSC | Output Power (W) with ideal Variable Capacitor |
|---|---|---|---|---|
| 6 | 0,400 | 40,1 | 161,6 | 164,7 |
| 8 | 0,533 | 53,8 | 291,2 | 295,1 |
| 10 | 0,667 | 67,7 | 461,7 | 466,4 |
| 12 | 0,800 | 74,2 | 554 | 558,1 |
| 14 | 0,933 | 88,2 | 781,7 | 786,6 |
| 16 | 1,067 | 101,6 | 1036,2 | 1041,2 |
| 18 | 1,200 | 114,4 | 1314,5 | 1320,3 |
| 20 | 1,333 | 127 | 1617,2 | 1623,8 |

As it is shown above the output power is very close to the ideal case, where the inductive reactance is equal to capacitive reactance, the system is at its resonant point and operates with maximum efficiency without any reactive losses. The downside is the use of numerous blocks m (anti-parallel thyristor shunted to a capacitor), especially as the frequency increases. In this case for 1.333Hz frequency 1627 blocks have been used, making this circuit non-attractive for further research at wind turbines.

Additionally, the switching devices can be controlled using an FPGA. The use of a computational system to control the switching devices is compulsory and the simplicity of the algorithm is beneficial for the reliability of the system. The low-level programming using a hardware descriptive language is using the advantages of the parallel processing and output of the data. Initial implementations are already providing positive feedback. A Cyclone V FPGA is more than capable to host the algorithm to control the switching device.

## 6 Conclusions

The paper describes the operation of a Thyristor Switched Series Capacitors (TSSC) circuit for wind turbines. A typical wind turbine uses a gearbox and in order to overcome the numerous problems of the usage of gearboxes and to improve the efficiency of a wind turbine, the usage of direct-drive systems was considered as the most appropriate method. The downside is that the electric frequency is not fixed and is much lower than 50Hz or 60Hz that the electric grid is required. Therefore, by using diode bridge rectifier, it is possible to convert the low variable AC signal to DC and then with an Inverter back to grid-required AC signal. However, this topology has low power factor due to high inductive reactance of the generator. Today the majority of the Wind Turbines employs a PWM rectifier to convert the variable ac signal to DC rather than a diode bridge rectifier, but such rectifiers have very high switching losses due to the high switching frequency [13].

This paper proposes the usage of controlled series compensation in order to compensate the inductive reactance of the generator. This technique even though is used in AC power transmission systems it has never been suggested for a variable-frequency, variable-voltage application such as in wind turbines.

A TSSC circuit has been studied, simulated and presented in this paper, in order to correct the converter’s operating power factor, over the whole of the operating frequency range. This will have as a result the maximisation of the wind turbine energy conversion.

Although the switching frequency of the Thyristors are kept low and specifically equal to the line frequency, keeping the switching losses to minimum compared to PWM rectifiers, this TSSC circuit uses high number of capacitors making it practically not feasible to be implemented for such projects. A way to overcome this problem is the use of Thyristor switched Parallel Capacitor TSPC. This new topology utilizes only one capacitor for every change in the system’s frequency. This circuit has been simulated using a standard diode bridge circuit and a 1.5kVA PMSG model. The performance characteristics are the same with the TSSC but this time the number of capacitors is drastically lower. The power factor achieved in simulations with the proposed TSPC circuit was near unity over the entire operating range, maximising the energy transfer from the machine to the load. The near future implementation will be hosted in an Intel – Altera FPGA device DE1.

## APPENDIX

PMSG parameters:

Maximum output volt-amperes: 1.5kVA
Maximum back EMF & Current: 230V/16A
Winding resistance: 6,4Ω
Winding inductance: 384mH

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