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ANALYSIS OF SMALL SIGNAL CHARACTERISTICS IN POWER SYSTEMS INCORPORATING WIND ENERGY AND ENERGY STORAGE UNITS

Dr. R. Shankar[*1], SD. Nagoor Babu[*2], SK. Khada Bhasha[*3], Y. Anil Kumar[*4]
[*1] Professor, Dept. of Electrical and Electronics Engineering.
[*2, 3, 4] Assistant Professor, Dept. of Electrical and Electronics Engineering.
A.M Reddy Memorial College of Engineering and Technology, Andhra Pradesh.

Abstract: This paper presents a comprehensive study of the small signal behavior of power systems, incorporating both wind generation units and energy capacitor systems (ECSs). The modeling of wind units, which feature squirrel-cage induction generators connected to the power system via a full-scale AC/AC converter, as well as the ECS unit, is elaborated upon in detail. The ECS unit, as considered in this study, is comprised of electric double-layer capacitors (EDLC) and a DC/AC converter. Through digital computer simulations, the small signal behavior of three test systems is thoroughly investigated and compared. These systems include: System S1: The WSCC 9-bus system equipped with three conventional synchronous generators (SGs). System S2: The WSCC system with one of the conventional SGs replaced by a wind energy system. System S3: Similar to S2, but with the addition of an ECS unit. The study encompasses a comparison of dominant eigenvalues, participant state variables, and related participation factors for each of the three systems. Furthermore, the paper delves into analyzing the effects of loading on the unstable modes of System S3, which incorporates conventional SGs, wind generation units, and ECS units, by examining the trajectory of these modes as loads are incrementally increased.

Keywords: Power Systems, Small Signal Behavior, Wind Generation

INTRODUCTION

WIND energy is one of the cheapest and cleanest sources of electrical energy. Installed capacity of wind power plants has increased from 59.3 GW in 2005 to 198 GW in 2010 with nearly $50 billion invested on wind energy in last 20 years [1]. Increased penetration of wind energy in power network is accompanied with deteriorated system dynamics (due to intermittent nature of wind speed), which should be taken into considerations. To compensate for these deteriorations new methods and equipment should be employed.It has been shown that energy storage systems can effectively improve power systems dynamics. In recent years, storage system capacity has been increased from tens of megawatt-hours to hundreds of megawatt-hours. In California a storage facility is going to be built that can deliver a full gigawatt to the grid for 4 to 6 hours. The ability of these sources to deliver/absorb large amount of power makes them a suitable choice for improving the dynamics of wind units and the overall power system. Several studies have been reported in literature related to output power smoothing of wind units connected to infinite bus using energy storage systems to compensate for wind speed fluctuations .However, effects of

power fluctuations of wind units on multi-machine power systems have not been investigated thoroughly.This project presents a study of small signal behavior of power systems including wind energy and energy capacitor systems (ECSs), which consists of electric double-layer capacitors (EDLC). The EDLC needs a simple charging mechanism and requires no protective circuits. Overcharging or over-discharging does not have negative effects on its lifespan, as it does on that of chemical batteries. For computer simulation three test systems are used. For test system 1, we use the WSCC 9-bus 3-machine system . For Test system 2, the synchronous generator at Bus 2 is replaced with a wind unit. For test system 3, we add an ECS unit to the test system
2. For each test system eigenvalues, participant variables, and participation factors are found and compared. Moreover, for the system containing wind and ECS units (test system 3), a thorough small signal analysis is performed. In next section, modeling of wind and ECS units are explained. Then state-space equation of the system is formed in
Section III. In Section IV, small signal characteristics of wind and ECS units are calculated and in Section V, small signal be-
haviors of three systems are compared.

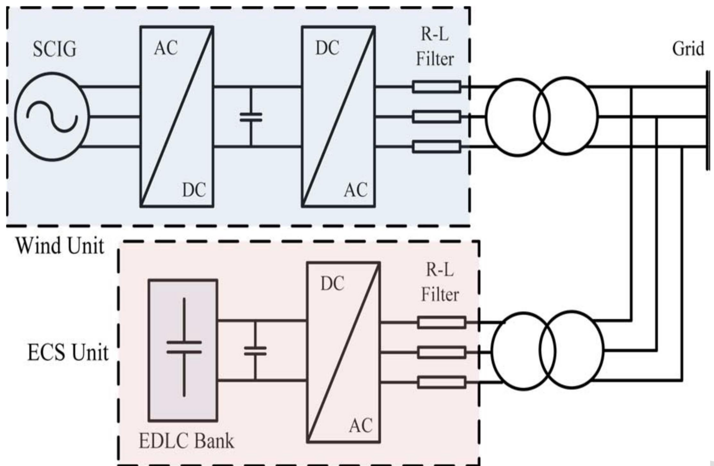
SYSTEM MODELING

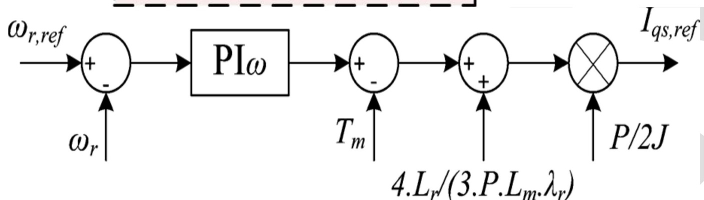
For performing small signal analysis different components of power system should be modeled first. For synchronous generators, one-axis model presented in is used. This model assumes one-mass steam turbine including four dynamic equations together with two algebraic equations. Each generator is assumed to be equipped with an IEEE DC-1A type exciter [18]. This exciter adds three more dynamic equations to the system.
Two other components, wind and ECS units, are shown in Fig. 1.

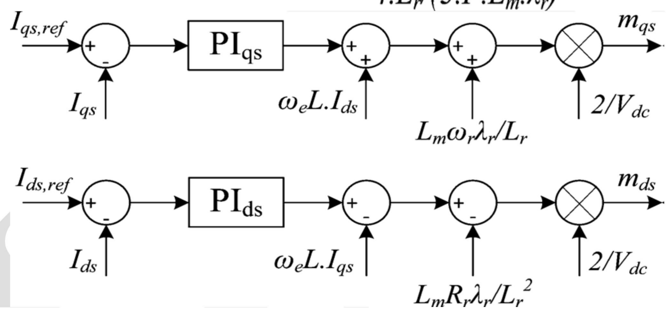
a) Modeling of Wind Unit: For wind unit, a squirrel-cage induction generator (SCIG) connected to the grid through a full-scale AC/AC converter (a combination of generator side AC/DC and grid side DC/AC converters) is used. Wind speed is modeled according to [19]. Dynamic equations of SCIG and the related converters are as follows [20]:

$$s\omega_r = \frac{P}{2J}(T_m + T_e) \tag{1}$$

$$sI_{qs} = \frac{1}{L_\sigma}\left(\frac{1}{2}m_{qs}V_{dc} - RI_{qs} - \omega_e L_\sigma I_{ds} - \frac{\omega_r L_m}{L_r}\lambda_r\right) \tag{2}$$







$$sI_{ds} = \frac{1}{L_\sigma}\left(\frac{1}{2}m_{ds}V_{dc} - RI_{ds} + \omega_e L_\sigma I_{qs} + \frac{R_r L_m}{L_r^2}\lambda_r\right) \quad (3)$$

$$sV_{dc} = \frac{3}{4C}(m_{qs}I_{qs} + m_{ds}I_{ds} + m_{qL}I_{qL} + m_{dL}I_{dL}) \quad (4)$$

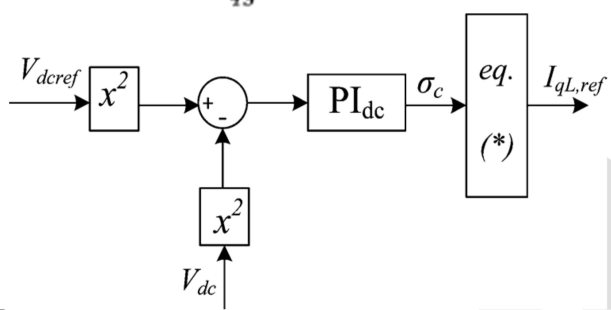
$$sI_{qL} = \frac{1}{L_f}\left(\frac{1}{2}m_{qL}V_{dc} - |V_g| - R_g I_{qL} - \omega_g L_g I_{dL}\right) \quad (5)$$

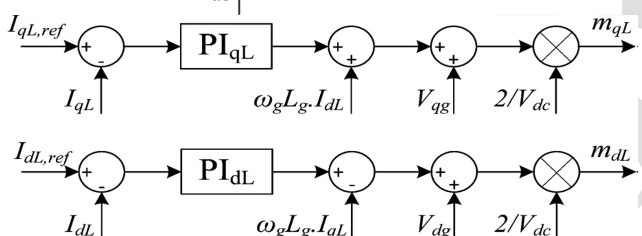
$$sI_{dL} = \frac{1}{L_f}\left(\frac{1}{2}m_{dL}V_{dc} - R_g I_{dL} + \omega_g L_g I_{qL}\right) \quad (6)$$

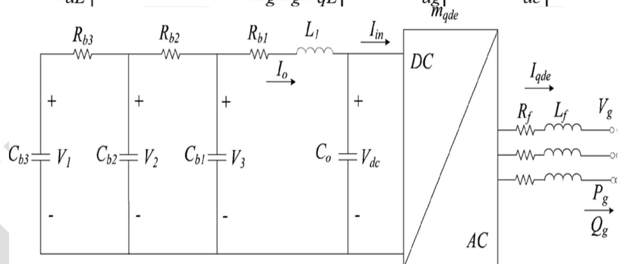
For generator-side converter, the control objectives are related to maximum power point tracking (MPPT) and indirect filed-orientation control. Based on these strategies block diagrams of rotor speed control loop (to achieve maximum power point) and generator-side current control loops are designed as Figs. 2 and 3, respectively.

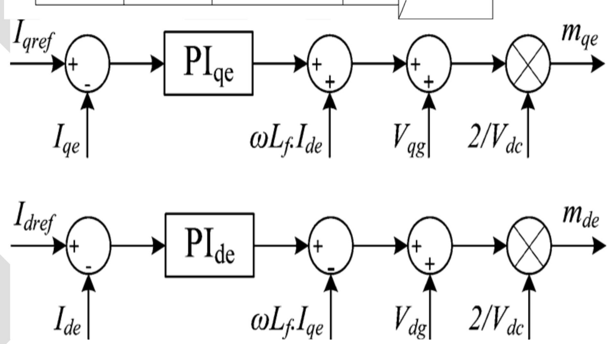
For grid-side converter, the control objectives are to maintain constant DC-link voltage and regulate the output reactive power of the wind unit. Fig. 4 shows block diagram of the DC-link voltage controller, and Fig. 5 shows block diagrams of the grid-side converter control loops. Equation (*) in Fig. 4 is defined as follows:

$$I_{qL,\mathrm{ref}} = \frac{2}{3V_{qg}}(\sigma_c - P_{\mathrm{in}} - P_{\mathrm{loss}})$$









b) Modeling of ECS Unit: Fig. 6 shows the schematic diagram of an ECS unit [20]. The control objectives for this unit are to regulate the output active and reactive powers of the unit through controlling the -and -axis components of the ECS output current according to (8) (current control loops are shown in Fig. 7):

$$\begin{cases} P_{\mathrm{ref}} = \frac{3}{2}|V_g|I_{q,\mathrm{ref}} \\ Q_{\mathrm{ref}} = -\frac{3}{2}|V_g|I_{d,\mathrm{ref}}. \end{cases} \qquad (8)$$

Definition of Alternator

The definition of alternator is hidden in the name of this machine itself. An alternator is such a machine which produces alternation electricity. It is a kind of generators which converts mechanical energy into alternating electrical energy. It is also known as synchronous generator.

History of Alternator

Michael Faraday and Hippolyte Pixii gave the very first concept of alternator. Michael Faraday designed a rotating rectangular turn of conductor inside a magnetic field to produce alternating current in the external static circuit. After that in the year of 1886 J.E.H. Gordon, designed and produced first prototype of useful model. After that Lord Kelvin and Sebastian Ferranti designed a model of 100 to 300 Hz synchronous generator. Nikola Tesla in 1891, designed a commercially useful 15 KHz generator. After this year, poly phase alternators were come into picture which can deliver currents of multiple phases.

Use of Alternator

The power for electrical system of modern vehicles produces from alternator. In previous days, DC generators or dynamos were used for this purpose but after development of alternator, the dc dynamos are replaced by more robust and light weight alternator. Although the electrical system of motor vehicles generally requires direct current but still an alternator along with diode rectifier instead of a DC generator is better choice as the complicated commutation is absent here. This special type of generator which is used in vehicle is known as automotive alternator. Another use of alternator is in diesel electric locomotive. Actually the engine of this locomotive is nothing but an alternator driven by diesel engine. The alternating current produced by this generator is converted to DC by integrated silicon diode rectifiers to feed all the dc traction motors. And these dc traction motors drive the wheel of the locomotive. This machine is also used in marine similar to diesel electric locomotive. The synchronous generator used in marine is specially designed with appropriate adaptations to the salt-water environment. The typical output level of marine alternator is about 12 or 24 volt. In large marine, more than one units are used to provide large power. In this marine system the power produced by alternator is first rectified then used for charging the engine starter battery and auxiliary supply battery of marine.

Types of Alternator

Alternators or synchronous generators can be classified in may ways depending upon their application and design. According to application these machines are classified as-

1. Automotive type - used in modern automobile.
2. Diesel electric locomotive type - used in diesel electric multiple unit.
3. Marine type - used in marine.
4. Brush less type - used in electrical power generation plant as main source of power.
5. Radio alternators - used for low brand radio frequency transmission.

These ac generators can be divided in many ways but we will discuss now two main types of alternator categorized according to their design. These are-

1. Salient pole type It is used as low and medium speed alternator. It has a large number of projecting poles having their cores bolted or dovetailed onto a heavy magnetic wheel of cast iron or steel of good magnetic quality. Such generators are characterized by their large diameters and short axial lengths. These generator are look like big wheel. These are mainly used for low speed turbine such as in hydral power plant.

2. Smooth cylindrical type It is used for steam turbine driven alternator. The rotor of this generator rotates in very high speed. The rotor consists of a smooth solid forged steel cylinder having a number of slots milled out at intervals along the outer periphery for accommodation of field coils. These rotors are designed mostly for 2 pole or 4 pole turbo generator running at 36000 rpm or 1800 rpm respectively.

Synchronous Generators

3-Phase Generator (or Motor) Principles

All 3-phase generators (or motors) use a rotating magnetic field.

In the picture to the left we have installed three electromagnets around a circle. Each of the three magnets is connected to its own phase in the three phase electrical grid.

As you can see, each of the three electromagnets alternate between producing a South pole and a North pole towards the centre. The letters are shown in black when the magnetism is strong, and in light grey when the magnetism is weak. The fluctuation in magnetism corresponds exactly to the fluctuation in voltage of each phase. When one phase is at its peak, the other two have the current running in the opposite direction, at half the voltage. Since the timing of current in the three magnets is one third of a cycle apart, the magnetic field will make one complete revolution per cycle.

Synchronous Motor Operation

The compass needle (with the North pole painted red) will follow the magnetic field exactly, and make one revolution per cycle. With a 50 Hz grid, the needle will make 50 revolutions per second, i.e. 50 times 60 = 3000 rpm (revolutions per minute).

In the picture above, we have in fact managed to build what is called a 2-pole permanent magnet synchronous motor. The reason why it is called a synchronous motor, is that the magnet in the centre will rotate at a constant speed which is synchronous with (running exactly like the cycle in) the rotation of the magnetic field.

The reason why it is called a 2-pole motor is that it has one North and one South pole. It may look like three poles to you, but in fact the compass needle feels the pull from the sum of the magnetic fields around its own magnetic field. So, if the magnet at the top is a strong South pole, the two magnets at the bottom will add up to a strong North pole.

The reason why it is called a permanent magnet motor is that the compass needle in the centre is a permanent magnet, not an electromagnet. (You could make a real motor by replacing the compass needle by a powerful permanent magnet, or an electromagnet which maintains its magnetism through a coil (wound around an iron core) which is fed with direct current).

The setup with the three electromagnets is called the stator in the motor, because this part of the motor remains static (in the same place). The compass needle in the centre is called the rotor, obviously because it rotates.

Synchronous Generator Operation

If you start forcing the magnet around (instead of letting the current from the grid move it), you will discover that it works like a generator, sending alternating current back into the grid. (You should have a more powerful magnet to produce much electricity). The more force (torque) you apply, the more electricity you generate, but the generator will still run at the same speed dictated by the frequency of the electrical grid.

You may disconnect the generator completely from the grid, and start your own private 3-phase electricity grid, hooking your lamps up to the three coils around the electromagnets. (Remember the principle of magnetic / electrical induction from the reference manual section of this web site). If you disconnect the generator from the main grid, however, you will have to crank it at a constant rotational speed in order to produce alternating current with a constant frequency. Consequently, with this type of generator you will normally want to use an indirect grid connection of the generator.

In practice, permanent magnet synchronous generators are not used very much. There are several reasons for this. One reason is that permanent magnets tend to become demagnetised by working in the powerful magnetic fields inside a generator. Another reason is that powerful magnets (made of rare earth metals, e.g. Neodynium) are quite expensive, even if prices have dropped lately.

Wind Turbines With Synchronous Generators

Wind turbines which use synchronous generators normally use electromagnets in the rotor which are fed by direct current from the electrical grid. Since the grid supplies alternating current, they first have to convert alternating current to direct current before sending it into the coil windings around the electromagnets in the rotor.

The rotor electromagnets are connected to the current by using brushes and slip rings on the axle (shaft) of the generator.

Induction generator

An induction generator or asynchronous generator is a type of alternating current (AC) electrical generator that uses the principles of induction motors to produce power. Induction generators operate by mechanically turning their rotors faster than synchronous speed. A regular AC asynchronous motor usually can be used as a generator, without any internal modifications. Induction generators are useful in applications such as mini hydro power plants, wind turbines, or in reducing high-pressure gas streams to lower pressure, because they can recover energy with relatively simple controls.

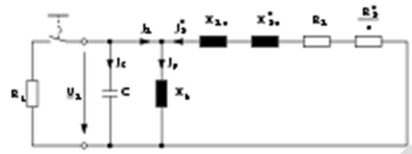
An induction generator usually draws its excitation power from an electrical grid; sometimes, however, they are self-excited by using phase-correcting capacitors. Because of this, induction generators cannot usually "black start" a de-energized distribution system.

Principle of operation

An induction generator produces electrical power when its rotor is turned faster than the synchronous speed. For a typical four-pole motor (two pairs of poles on stator) operating on a 60 Hz electrical grid, the synchronous speed is 1800 rotations per minute (rpm). The same four-pole motor operating on a 50 Hz grid will have a synchronous speed of 1500 RPM. The motor normally turns slightly slower than the synchronous speed; the difference between synchronous and operating speed is called "slip" and is usually expressed as per cent of the synchronous speed. For example, a motor operating at 1450 RPM that has a synchronous speed of 1500 RPM is running at a slip of +3.3%.

In normal motor operation, the stator flux rotation is faster than the rotor rotation. This causes the stator flux to induce rotor currents, which create a rotor flux with magnetic polarity opposite to stator. In this way, the rotor is dragged along behind stator flux, with the currents in the rotor induced at the slip frequency.

In generator operation, a prime mover (turbine or engine) drives the rotor above the synchronous speed (negative slip). The stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, an active current is produced in stator coils and the motor now operates as a generator, sending power back to the electrical grid.
Excitation



Equivalent circuit of induction generator
An induction machine requires externally supplied armature current; it cannot start on its own as a generator. Because the rotor field always lags behind the stator field, the induction machine always "consumes" reactive power, regardless of whether it is operating as a generator or a motor.
A source of excitation current for magnetizing flux (reactive power) for the stator is still required, to induce rotor current. This can be supplied from the electrical grid or, once it starts producing power, from the generator itself.

Active power

Active power delivered to the line is proportional to slip above the synchronous speed. Full rated power of the generator is reached at very small slip values (motor dependent, typically 3%). At synchronous speed of 1800 rpm, generator will produce no power. When the driving speed is increased to 1860 rpm (typical example), full output power is produced. If the prime mover is unable to produce enough power to fully drive the generator, speed will remain somewhere between 1800 and 1860 rpm range.

Required capacitance

A capacitor bank must supply reactive power to the motor when used in stand-alone mode. The reactive power supplied should be equal or greater than the reactive power that the machine normally draws when operating as a motor. Terminal voltage will increase with capacitance, but is limited by iron saturation.
Torque vs. slip
The basic fundamental of induction generators is the conversion between mechanical energy to electrical energy. This requires an external torque applied to the rotor to turn it faster than the synchronous speed. However, indefinitely increasing torque doesn't lead to an indefinite increase in power generation. The rotating magnetic field torque excited from the armature works to counter the motion of the rotor and prevent over speed because of induced motion in the opposite direction. As the speed of the motor increases the counter torque reaches a max value of torque (breakdown torque) that it can operate until before the operating conditions become unstable. Ideally, induction generators work best in the stable region between the no-load condition and maximum torque region.

Maximum pass-through current

In practice and without taking this notion into account, many users unsuccessfully apply the principles to the actual deployment.

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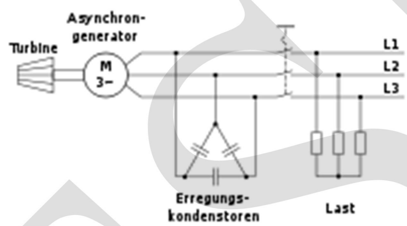
It's not in popular belief; that in almost every case, under the same active grid voltage, the power that the generator produces is greater than the power it consumes when it is at the motor,fully loaded state; its rated power. Sometimes the differences are in multiple folds. Higher the power means higher the amperage.
For prolong operation, and implied in its guaranteed , each motor has its "maximum pass-through current". This amperage value; the current density; is derived from the maximum pass-through current property of the internal copper magnet wire and the combined configuration of their connections. Without opening up the unit to examine the internal setting of the copper wires, a division of the wattage of its rated power by its rated voltage can give users some senses of how much that value is.
Therefore claims of making a unit generates more power than its rated should get a closer examination.

Grid and stand-alone connections



Typical connections when used as a standalone generator
In induction generators, the reactive power required to establish the air gap magnetic flux is provided by a capacitor bank connected to the machine in case of stand-alone system and in case of grid connection it draws reactive power from the grid to maintain its air gap flux. For a grid-connected system, frequency and voltage at the machine will be dictated by the electric grid, since it is very small compared to the whole system. For stand-alone systems, frequency and voltage are complex function of machine parameters, capacitance used for excitation, and load value and type.
Use of induction generators
Induction generators are often used in wind turbines and some micro hydro installations due to their ability to produce useful power at varying rotor speeds. Induction generators are mechanically and electrically simpler than other generator types. They are also more rugged, requiring no brushes or commutators.
Induction generators are particularly suitable for wind generating stations as in this case speed is always a variable factor. Unlike synchronous motors, induction generators are load-dependent and cannot be used alone for grid frequency control.
Example application
As an example, consider the use of a 10 hp, 1760 r/min, 440 V, three-phase induction motor as an asynchronous generator. The full-load current of the motor is 10 A and the full-load power factor is 0.8.
Required capacitance per phase if capacitors are connected in delta:

Apparent power $S = \sqrt{3}\,E\,I = 1.73 \times 440 \times 10 = 7612$ VA

Active power $P = S \cos\theta = 7612 \times 0.8 = 6090$ W

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Reactive power Q = $\sqrt{S^2 - P^2}$ = 4567 VAR

For a machine to run as an asynchronous generator, capacitor bank must supply minimum 4567 / 3 phases = 1523 VAR per phase. Voltage per capacitor is 440 V because capacitors are connected in delta.

Capacitive current Ic = Q/E = 1523/440 = 3.46 A

Capacitive reactance per phase Xc = E/Ic = 127 Ω

Minimum capacitance per phase:

C = 1 / (2*π*f*Xc) = 1 / (2 * 3.141 * 60 * 127) = 21 microfarads.

If the load also absorbs reactive power, capacitor bank must be increased in size to compensate.
Prime mover speed should be used to generate frequency of 60 Hz:
Typically, slip should be similar to full-load value when machine is running as motor, but negative (generator operation):

if Ns = 1800, one can choose N=Ns+40 rpm

Required prime mover speed N = 1800 + 40 = 1840 rpm.

AC machines can be further classified as Induction machines and Synchronous machines. And hence, AC generators as Synchronous generators (commonly referred as alternators) and Induction generators (or asynchronous generators).

There is significant difference between operating principles of synchronous and induction machines. For now, let us discuss the difference between synchronous generator and induction generator.
Difference between synchronous generator and induction generator

- In a synchronous generator, the waveform of generated voltage is synchronized with (directly corresponds to) the rotor speed. The frequency of output can be given as f = N * P / 120 Hz. where N is speed of the rotor in rpm and P is number of poles.

  In case of inductions generators, the output voltage frequency is regulated by the power system to which the induction generator is connected. If induction generator is supplying a standalone load, the output frequency will be slightly lower (by 2 or 3%) that calculated from the formula f = N * P / 120.
- Separate DC excitation system is required in an alternator (synchronous generator).

  Induction generator takes reactive power from the power system for field excitation. If an induction generator is meant to supply a standalone load, a capacitor bank needs to be connected to supply reactive power.
- Construction of induction generator is less complicated as it does not require brushes and slip ring arrangement. Brushes are required in synchronous generator to supply DC voltage to the rotor for excitation.

Energy Storage

The energy stored is related to the charge at each interface, q (Coulombs) , and potential difference, V (Volts), between the electrodes. The energy, E (Joules), stored in a capacitor with capacitance C (Farads) is given by the following formula.

$E = ½ q V = ½ CV^2$

See What can a Joule do? for an example.

Since capacitors store charge only on the surface of the electrode , rather than within the entire electrode, they tend to have lower energy storage capability and lower energy densities. The charge/discharge reaction is not limited by ionic conduction into the electrode bulk, so capacitors can be run at high rates and provide very high specific powers but only for a very short period. Typical numbers for capacitors and batteries are given below:

Capacitor / Battery Comparison

Device	Energy density Wh/L	Power density W/L	Cycle life Cycles	Discharge time Seconds
Batteries	50-250	150	$1 - 10^3$	> 1000
Capacitors	0.05 - 5	$10^5 - 10^8$	$10^5 - 10^6$	<1

Typical Coulombic efficiency is around 90%

See also examples of the relative energy storage capacities of capacitors and batteries in the section on Short Circuits.

Since there is no chemical reactions are involved, the charge/discharge reactions can typically be cycled many more times than batteries (10^8 cycles per device have been achieved). For the same reason, capacitors don't require any special charging circuits and cells can be designed to accept very high voltages, although for very high capacities the working voltage is limited to a few volts.

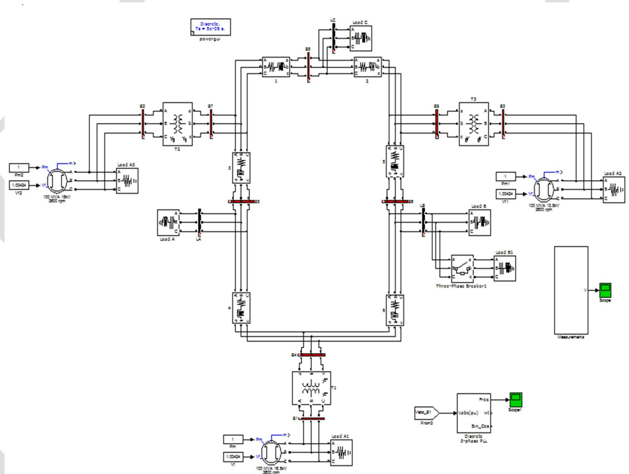
Supercapacitors are simply capacitors employing plates with extremely high surface areas providing a high storage capacity. Maximizing the surface area of the electrodes within the available space means the thickness of the dielectric must be minimised. This in turn limits the maximum working voltage of the capacitor. For this reason, even though there is no fixed limit, set by the chemistry, on the working voltage of a capacitor as there is with batteries, for supercapacitors with a capacitance of over 1000 Farads or more the working voltage may be only a few volts.

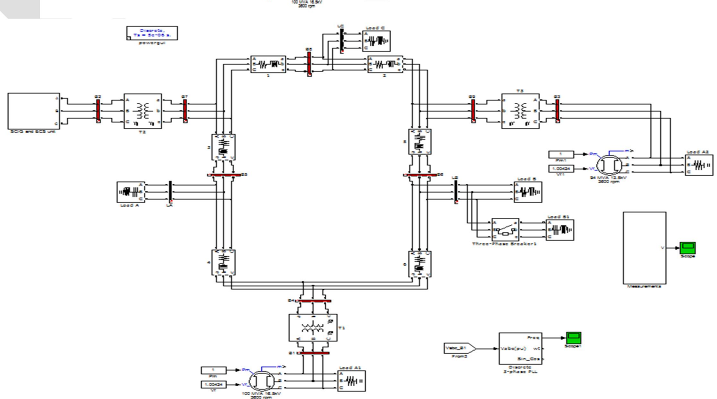
For high voltage applications such as electric vehicles, a series chain of capacitors must be used to avoid exceeding the working voltage of individual capacitors and this reduces the effective capacity of the chain. For a series chain of N equal value capacitors the capacity is calculated from C=c/N where C is the capacitance of the chain and c is the capacitance of the individual capacitors. At the same time, the internal resistance of the chain is increased to R=rN, where r is the internal resistance of the capacitor, as more capacitors are added. This slows the charge-discharge rate and increases the losses.

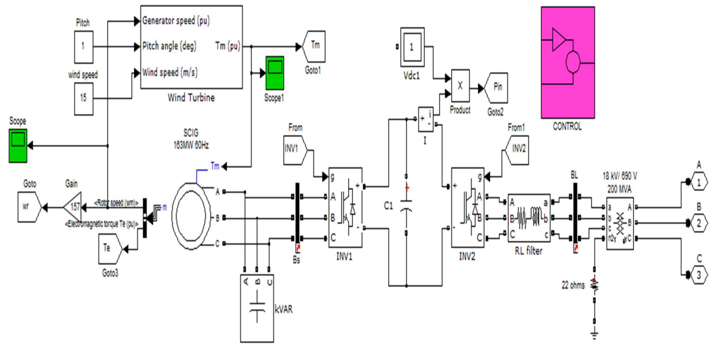
Higher capacitances can be achieved by using parallel capacitors. In this case the capacitance of a group of N parallel capacitors is given by C=Nc. At the same time the resistance of the group is reduced and is given by R=r/N.

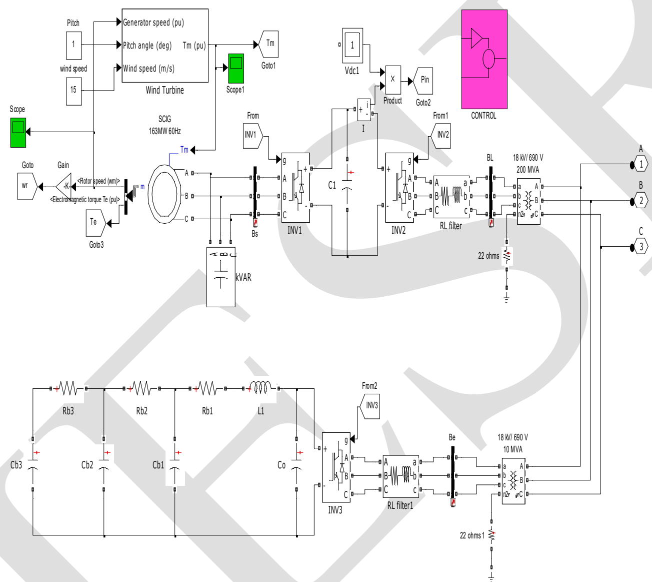
Capacitors are now used extensively as power back up for memory circuits and in conjunction with batteries to provide a power boost when needed. See Load sharing.
High power versions can provide high instantaneous power but they have limited capacity. See the Ragone Plot below. They are suitable for applications which require a short duration power boosts such as UPS systems which need fast take over of substantial electrical loads for a short period until back up power units, such as rotary generators or fuel cells, have switched on and reached their full output. Similarly they can be used to provide an instantaneous power boost in Electric and Hybrid vehicles.
Supercapacitors are however also ideal for absorbing the energy generated from regenerative braking in EVs and HEVs since they can accept very high instantaneous charge rates which would exceed the recommended maximum charge rate of the batteries. Used in conjunction with batteries the capacitors enable the full regenerative charge to be captured, avoiding the wasteful dumping of the excess charge which the batteries are unable to accommodate.
See more in the section on Capacitors and Supercapacitors.

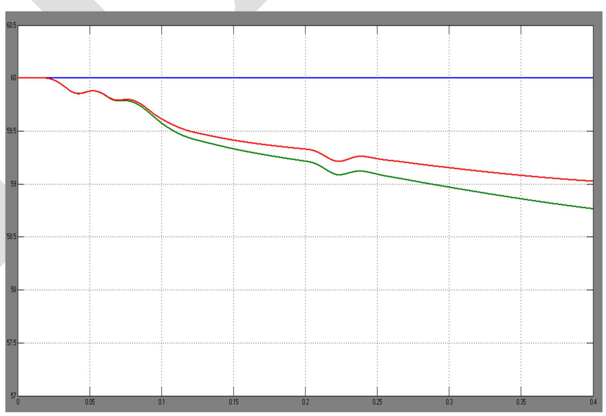
SIMULINK RESULTS AND OUTPUTS











CONCLUSION

In this paper, small signal stability of a power system including wind and ECS units was studied and compared with two other systems: a system with only conventional sources and a system with wind generation but without any ECS unit. Also, effect of loading on unstable modes of this system was investigated.The results show that while replacing a synchronous machine with a wind unit has negative effect on loadability of the system, addition of ECS unit can increase the loadability (or transmission capacity). The increased loadability is even more than the original system having synchronous generators only. In addition, from the simulation results it was found that wind units (in a system without ECS) do not participate at unstable modes (or eigenvalue) of the system, but after adding ECS unit to the system both ECS and wind units cause unstable eigenvalues.In common practice (as reported in literature), the main purpose of using ECS unit is to smooth the output power of wind units. Based on the results of this research, it can be concluded that adding ECS can also enhance the stability and/or loadability of the overall system. This is an additional benefitofusingECS together with wind generation.

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