Power Augmentation of Inverter by Vector Modulation Control in Super Capacitor Integrated Hybrid System

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***Abstract*: For energy systems in distant and isolated communities, a self-sufficient energy scheme based on renewable energy can be a mainly stimulating and frugally beneficial solution, since the development of the network is frequently unfeasible because of monetary and technical constraints. In this research work, I designed a hybrid (Solar-PV) system with Wind energy scheme in as to augment its output capacity before its incorporation with the grid. Also the scheme is incorporated with a SC (Super Capacitor) exemplary for handling the modification in the power demand of the scheme. The inverter has been modeled with Vector Modulation method which has brought about in more smooth and improved output consequence when used in amalgamation with DC output potential. It was determined that magnitude of active power output is improved from the scheme having inverter with Vector Modulation control as compared to the scheme having inverter with simple PM (Pulse Modulation) control. Although calculating the RMS (Root Mean Square) value of the real power it was found to be around 5000 VA and less pulsating than that of power output from the inverter having PM (Pulse Modulation) Control. Also computational approach of the suggested modulation method is very easy and the system can be pragmatic to multilevel inverter with any number of levels.**

***Keywords*: Wind-Energy Conversion System (WECS), Super Capacitor (SC), Doubly-Fed Induction Generator (DFIG), Squirrel-Cage Induction Generator (SCIG)**

I. INTRODUCTION

Because of the rapid evolution and challenges related to the distribution, production and use of energy, renewable energy expertise's can play an significant role in the imminent supply of electricity thanks to the raised consciousness of environmental pollution. For energy systems in distant and distant communities, an independent energy system based on renewable-energy can be a specificallyinteresting and economically beneficial solution, meanwhile the expansion of the network is regularly impractical because of technical and economic constraints. Generators (Diesel) are most frequently used as independent power system applications in distant and inaccessible communities owing to their reliability, inexpensive installation, tranquil commissioning, condensed power density and portability. The rise in fuel prices, though, makes them very costly.

Wind Energy Conversion System

In the last years, wind generation schemes have intimate with marvelous growth and been familiar as an alternate environmentally-friendly and price-effectual means of power generation. The notable elements of a classic wind-energy conversion system (WECS) contain a turbine, generator and control systems. Fig. 1 shows a WECS. The generators conventionally employed in WECSs are the DFIG, cage induction generator, and synchronous generators. The power electronics agree to a successive convertor. The WECS are often associated to an oversized utility, a micro-grid (weak grid), or a complete load.

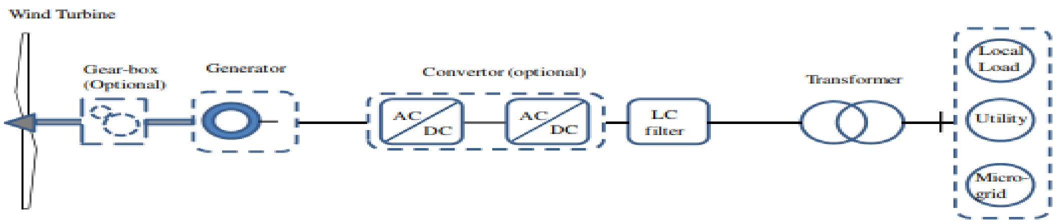

Figure: 1- Wind Energy Conversion System

DFIG- Based WECS

The DFIG is mostly employed for variable-speed generation and is a standout among the most vigorous generators for wind-vitality applications. The DFIG (Doubly-Fed Induction Generator) based WECS (Wind Energy Conversion System) is seemed in Fig. 2. These days, the DFIG-based wind turbine signifies about half of wind-energy market share. For a usual DFIG, a successive power converter is connected with the rotor for a confined speed range of operation, usually 30% of its rated value. In DFIG (Doubly-Fed Induction Generator) based WECS (Wind Energy Conversion System), slip-rings associate the machine-side converter to rotor, and gear boxes are similarly essential, since a multi-pole low-speed DFIG isn't really attainable.

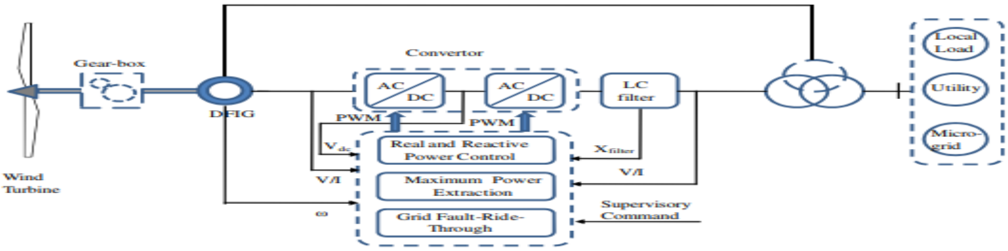

Figure: 2- DFIG-based WECS

SCIG-based WECS

The SCIG (Squirrel-Cage Induction Generator) appeared in Fig. 3 is a protuberant machine because of its mechanical straight-forwardness and strong growth. In contrast to the Doubly-Fed IG, no brushes are obligatory for the machine's task. Minimal preservation is important, aside from bearing oil. The SCIG (Squirrel-Cage Induction Generator) was usually utilized in fixed-speed WECS (first Danish breeze turbines), and it is as yet employed for variable-speed wind-energy age. The IG (Induction Generator) with a frequency-converter is totally decoupled from the grid; accordingly this frame-work has a total network connotation capacity.

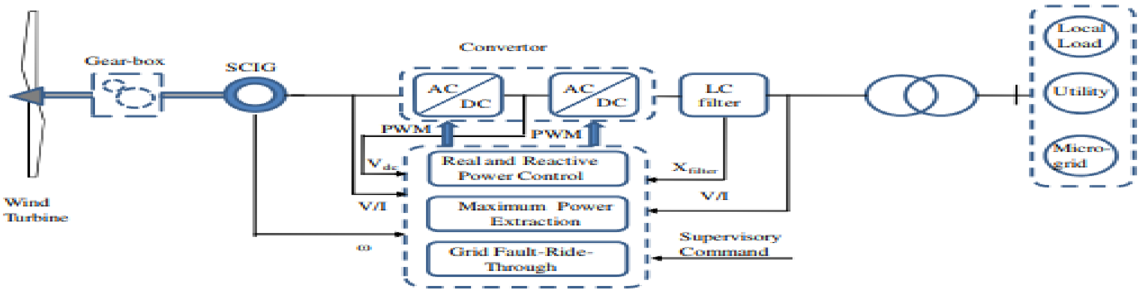

Figure: 3- SCIG-based WECS

II. AIMS AND OBJECTIVES

There are subsequent aims and objectives are to be anticipated from the contemporaneous work:-

- Designing a hybrid solar-Photovoltaic scheme with Wind Energy System (WES) in MATLAB/SIMULINK, so as to augment its output capacity before its integration with grid. Similarly the scheme has to be combined with a SC (Super Capacitor) model for handling the change in the power demand of the system.
- To design an appropriate controller for the 3-leg Universal Bridge converter such that it produces improved output outcomes than the traditional PM (Pulse Modulation) technique.
- The controller has to be designed with Vector Modulation method, simple in implementation and operation.
- Augment the scheme trustworthiness and efficacy by integrating it with the grid via a transformer with the anticipated grid potential and frequency.

III. METHODOLOGY

Modeling of PV module

Photovoltaic (PV) cells have solitary working point where the approximations of the current (I) and potential (V) of the cell consequence in an utmost extreme power output. These wherewithals compare to an explicit antagonism, which is the same to Potential/current.

The MPPT (Maximum Power Point Tracking) calculation has been employed so as to attain the action of solar powered-module at greatest power output. P and O scheme has been carried into utilization.

A cell R_s (Series Resistance) is allied in series with parallel amalgamation of cell I_{ph} (photo-Current), D (Exponential Diode), and R_{sh} (Shunt Resistance) , Ipv is the cell current and Vpv is the cells voltage respectively. It can be conveyed as:

$$I_{pv} = I_{ph} - I_s\left(e^{q(V_{pv}+I_{pv}*R_s)/nKT} - 1\right) - (V_{pv} + I_{pv} * R_s)/R_{sh} \quad (1)$$

Where:

I_{ph} is the Solar-induced current

I_s is the diode saturation current

Q is the Electron charge ($1.6e^{-19}$C)

K is Boltzmann constant ($1.38e^{-23}$J/K)

n is the ideality factor (1~2)

T is the Temperature in ^{0}K

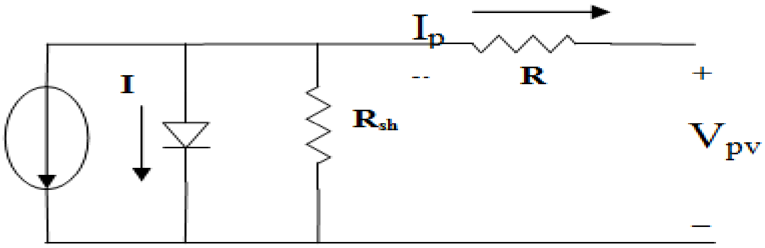

Figure: 4- Equivalent Circuit of Solar PV Cell

The solar induced current (I_{ph}) of the solar PV cell be determined by on the solar irradiation level and the working temperature can be articulated as:

$$I_{ph} = I_{sc} - k_i(T_c - T_r) * \frac{I_r}{1000} \quad (2)$$

Where:
I_{SC} is the short-circuit current of cell at STC
k_i is the cell short-circuit current/temp coefficient (A/K)
I_r is the Irradiance in w/m^2
T_c,T_r are the cell working and reference temperature at STC
A PV (Photovoltaic) cell has an exponential rapport amid potential and current and the MPP (Maximum Power Point) ensue at the knee of the curve as presented in the Fig 5.

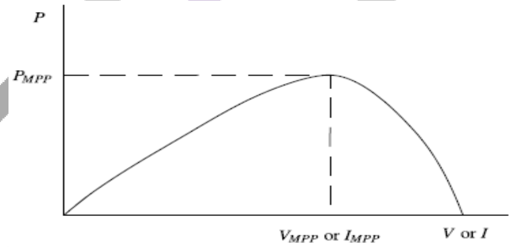

Figure: 5- Characteristic PV Array Power Curve

The O&P deviousness will follow the most extreme power to supply the DCMGs (Direct Current Micro grids) frame-work. The conventions for exemplary derivation are that the impeccable current source can be demonstrated as the PVs (Photovoltaic) activities. As well, all power converters are drove under the CCM (Continuous Conduction Mode) and the harmonics are in addition flouted.

Modeling of Wind Energy System
Exemplary of wind turbine with PMSG (Permanent Magnet Synchronous Generator) Wind turbines cannot fully incarceration wind energy. The constituents of wind turbine have been sculpted by the subsequent calculations or equations [8-10].

Output aerodynamic power of the wind-turbine is articulated as:

$$P_{Turbine} = \frac{1}{2}\rho A C_p(\lambda, \beta)v^3 \quad (3)$$

Where,
Air density ρ (typically 1.225 kg/m^3),
Area swept by the rotor blades *"A"* (in m^2),
Coefficient of power conversion *CP*,
Wind speed *v* (in m/s).

The tip-speed ratio is well-defined as:

$$\lambda = \frac{\omega_m R}{v} \quad (4)$$

Where,
ω_m is the rotor angular velocity (in rad/sec),
R is the rotor radium (in m), correspondingly.
T_m is the wind turbine mechanical torque output given as:

$$T_m = \frac{1}{2}\rho A C_p(\lambda, \beta)v^3 \frac{1}{\omega_m} \quad (5)$$

The CP (power coefficient) is a non-linear function of λ tip speed ratio and β is blade pitch angle (in degrees).
Then, Power output is certain by,

$$P_{Turbine} = \frac{1}{2}\rho A C_{p_{max}} v^3 \quad (6)$$

A common equation is employed to demonstration the CP (power coefficient) reliant on the demonstrating turbine features represented in [2], [7-9] and [11] as:

$$C_p = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{-\left(\frac{21}{\lambda_i}\right)} \quad (7)$$

For each wind speed, there be real a specific point in the wind generator control characteristic, MPPT (Maximum Power Point Tracking), where the output power is enhanced. In this manner, the control of the WECS (Wind Energy Conversion System) load consequences in a variable-speed action of the turbine rotor, so the utmost power is taken relentlessly from the wind (Maximum Power Point Tracking control).

Modeling of Super Capacitor

It is significant that under the diversities of solar irradiance and wind speed, the powers fed to the usual DC attach from the WTG (Wind Turbine Generator) and PV (Photovoltaic) cluster may be meaningfully equivocated. In order to smooth down the power vagaries and, thus, smother them from replacing to the AC grid, the intensity of the SC (Super capacitor) should be bring about to make up for the power dissimilarities.

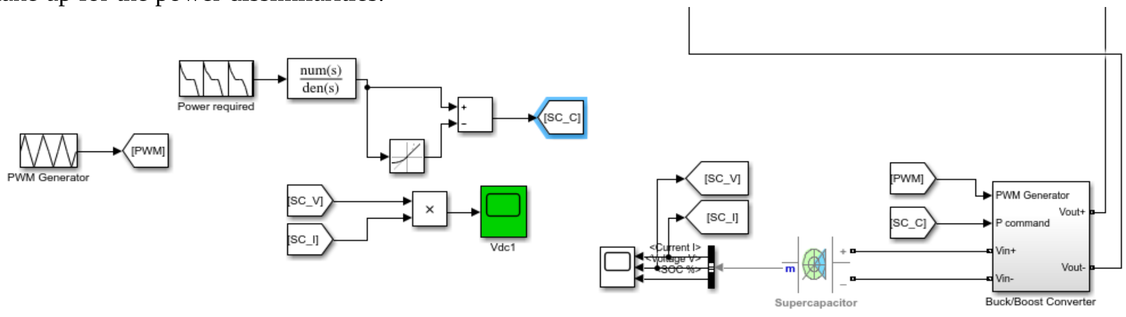

Figure: 6- MATLAB/SIMULINK Model of Super Capacitor

To attain this aim or objective, the reference value SC_C of the power control loop can be controlled by employing be an average of scheme as demarcated in Fig.

The SC (Super Capacitor) is allied with a Buck-Boost converter. Strength of the capacitor is limited by a rate-limiter square; alongside these lines the transient power is on condition that to the DC bus by the SC (Super Capacitor).

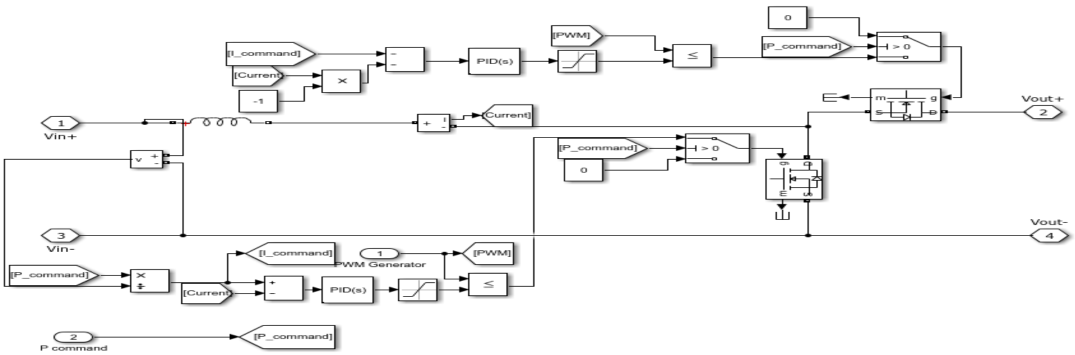

Figure: 7- Buck-Boost Converter Control in MATLAB

The movement of energy from or to buffer must be controlled rendering to necessities of power management. The converter works one or the other in Boost-mode throughout energy conveying from buffer to DC line or in Buck throughout buffer charging. Buck-mode has an output potential U_{OUT} is lesser than the potential input U_{IN} and output potential can be considered by subsequent formulation:

$$U_{OUT} = D.U_{IN} \quad (8)$$

Where,

$D=t_{ON}/T$ duty cycle

In boost-mode both potential (U_{IN} and U_{OUT}) are adjustable and the output potential must be controlled to accomplish constant potential. Output potential is premeditated rendering to follow formulation:

$$U_{OUT} = \frac{U_{IN}}{1-D} \quad (9)$$

Vector Modulation

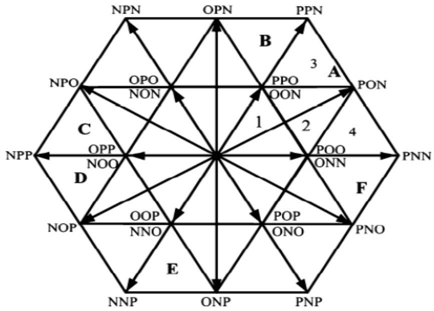

Figure: 8- Space-Vector Illustration of 3-Level Converter

Presumptuous the prompt potential value of 3-phase sine wave is correspondingly:

$U_a = V_m Sin(wt)$ (10)

$U_b = V_m Sin(wt - 2\pi/3)$ (11)

$U_c = V_m Sin(wt + 2\pi/3)$ (12)

The angle and magnitude of the rotating vector can be set up as below:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \quad (13)$$

$\vec{V}_{ref} = V_\alpha + jV_\beta = \frac{2}{3}(U_a + aU_b + a^2 U_c)$(14)

a= $e^{j2\pi/3}$ (15)

$$|\overrightarrow{V_{ref}}| = \sqrt{V_\alpha^2 + V_\beta^2}\ ,\ \theta = \tan^{-1}(V_\beta/V_\alpha) \quad (16)$$

If θ is amid 0° ≤θ< 60°, then V_{ref} will be in Sector A.
If θ is amid 60° ≤θ< 120°, then V_{ref} will be in Sector B.
If θ is amid 120° ≤θ< 180°, then V_{ref} will be in Sector C.
If θ is amid 180° ≤θ< 240°, then V_{ref} will be Sector D.
If θ is amid 240° ≤θ< 300°, then V_{ref} will be Sector E.
If θ is amid 300° ≤θ< 360°, then V_{ref} will be Sector F.

The major alleged of the amended calculation is the way by which to achieve the Calculation Flow reliant on one sector sooner than six as displayed in Fig. 9, just by appreciating the acquaintances in D_{well} Time computations and prearrangement for switches amid the first sector and the others as simplified underneath:

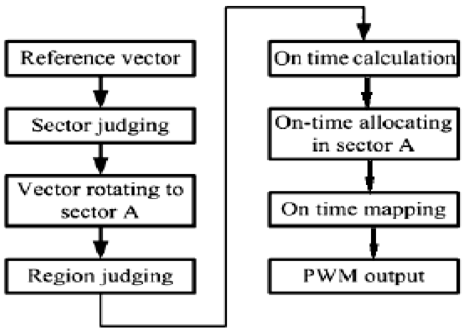

Figure: 9- Calculation Flow for 3-level SVPWM Simplified Calculation

Assume reference vector-A stays in region-2 of sector-A, whereas reference vector-B is attained by rotating vector-A counter clock-wise by 60° as revealed in Fig .10

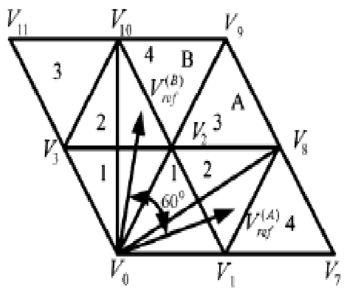

Figure: 10- Two Vectors with 60° Shifting in Sector-A and B.

So, the reference vector V_{ref} can be conveyed in the subsequent form.

$$V_{ref}^{B} = V_{ref}^{A} * e^{\frac{j\pi}{s}} = \frac{2}{3}(-U_b - U_c e^{\frac{2j\pi}{s}} - U_a e^{\frac{-2j\pi}{s}}) \quad (17)$$

And when the reference vector is in the extra sectors, it will be rotated to sector-A by $n\pi/3$ where (n = 1, 2, 3, 4, 5). The analogous reference vector in extra sectors can be erected as certain in Table: 1.

Table: 1- Associations of Potentials Constructing Reference Vectors in 6-Sectors.

Sectors	Phase Potential A	Phase Potential B	Phase Potential C
A	U_a	U_b	U_c
B	$-U_b$	$-U_c$	$-U_a$
C	U_c	U_a	U_b
D	$-U_a$	$-U_b$	$-U_c$
E	U_b	U_c	U_a
F	$-U_c$	$-U_a$	$-U_b$

IV. RESULTS

The investigation of the exemplary has been done in MATLAB/SIMULINK. MATLAB consolidates a work area state tuned for iterative research and design progression with a language of programming that lead into matrix and array science candidly. It facilitates graphical programming to edifice your frame-work in a simulation milieu.

In this exertion, Wind and Solar energy control a frame-work has been showed together to exaltation the consistency of the whole DG (Distributed Generation) frame-work. As well, this design allows the two sources to supply the load self-sufficiently or at the same time liable upon the availability of the vivacity sources.

Solar Powered Cell Model

The solar system entails of an adaptive MPPT (Maximum Power Point Tracking) algorithm with agitate and perceive [P&O] has been executed. Figure below shows the MPPT (Maximum Power Point Tracking) potential and MPPT (Maximum Power Point Tracking) power when the exemplary is simulated for 2-seconds. The consequence of solar section is providing as input to DC/DC boost-converter which is an average appreciated Buck-converter.

"Duty-cycle" of this converter entail of internal IGBT (Insulated-Gate Bipolar Transistor) device. The SC (Super Capacitor) aids the scheme by supplying/storage extreme power to DC-grid all through heavy/low load conditions.

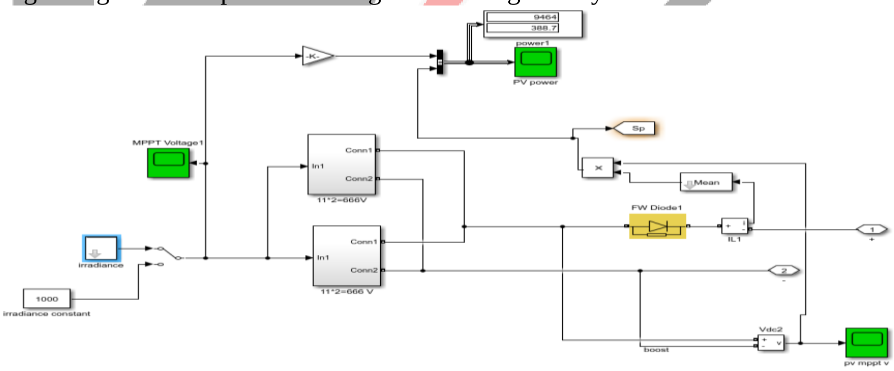

Figure: 11- Solar System Model

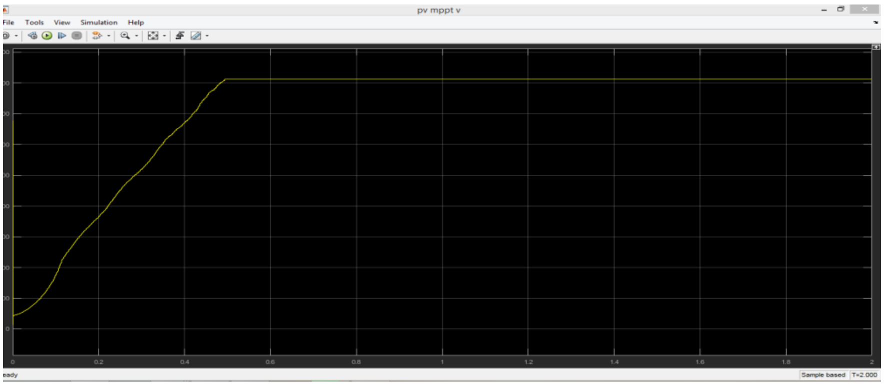

Figure: 12- Solar System Voltage Output

Wind system Model

PMSG (Permanent Magnet Synchronous Generator) has been demonstrated having stator-phase resistance 0.425 Ω, armature inductance 0.000395 Henry, and Pole Pairs five. The torque (base input) is taken to be 152.89 Newton-meter. The table (below) displays a number of scheme parameters that has been demonstrated in wind energy scheme by means of MATLAB/SIMULINK.

Table: 2- Parameters of Wind Energy System (WES)

Wind Turbine Exemplary	
Nominal Mechanical Power Output (Watt)	$8.5e^3$
Base Wind Speed (meter/sec)	12
Max. Power at Base Wind Speed (p.u)	0.8
Base Rotational Speed (p.u)	1
Permanent Magnet (PM) Synchronous Machine	
Stator Phase Resistance R_s (Ω)	0.425
Armature Inductance (Henry)	0.000395
Flux Linkage	0.433
Pole Pairs	5

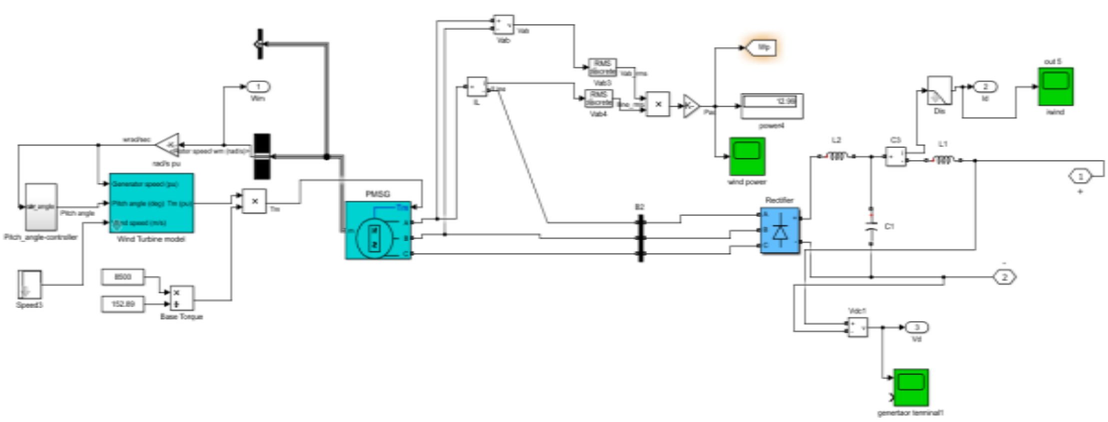

Figure: 13- Wind System Exemplary

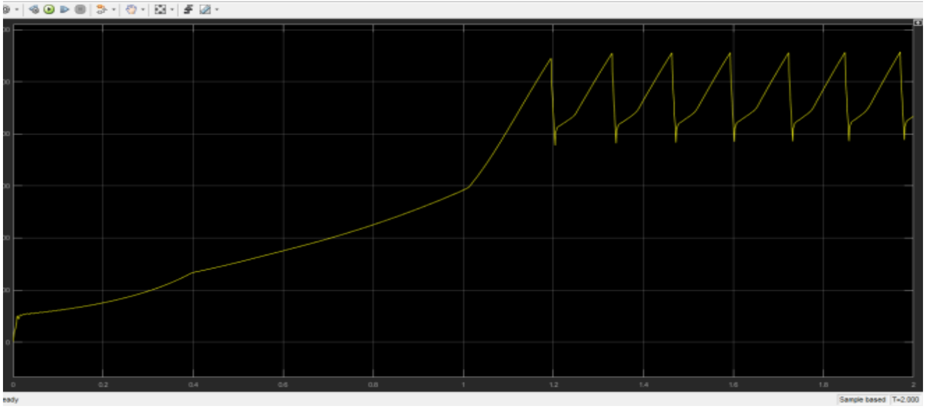

Figure: 14- Wind Energy System Voltage Output

Outputs from Inverter Modeling

Case 1:System Exemplary With Pulse Modulation:

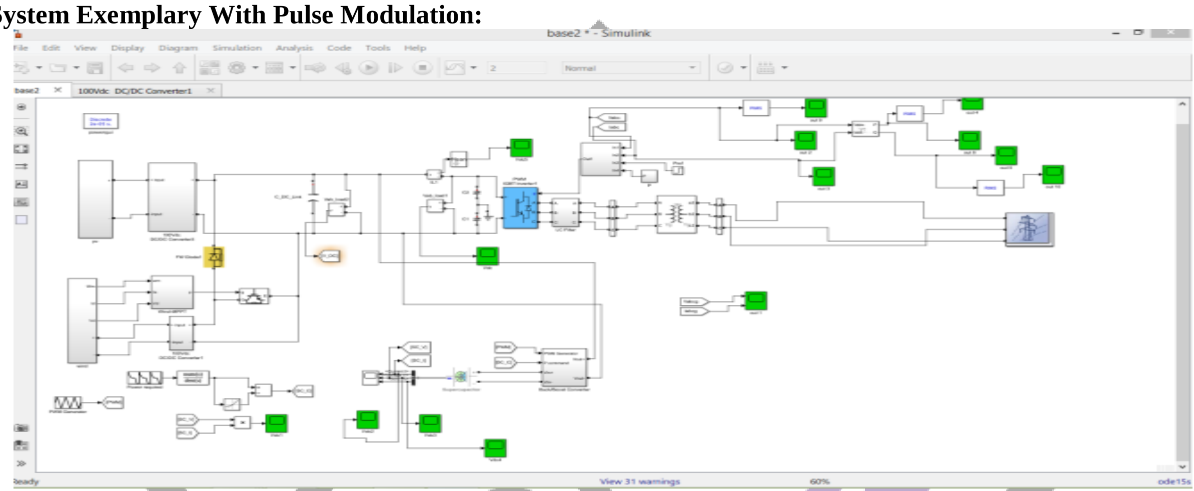

Figure: 15- System Exemplary With Pulse Modulation

The potential and current outputs figure is in use as the reference for generating pulses. Then their powers (reactive and active) have been premeditated to be fed into a Proportional Integral (PI) controller that is allied to a PWM (Pulse Width Modulation) generator. PWM (Pulse Width Modulation) generator will in turn generate pulses for the 4-leg modeled IGBT (Insulated-Gate Bipolar Transistor) converter. P (Proportional) gain K_p of the PI (Proportional Integral) controller is kept to be 0.1 and the I (Integral) gain K_i is kept to be 1. The snubber resistance of inverter is kept to be 5000 Ω.

The input DC potential to the inverter which is being demonstrated with PM (Pulse Modulation) has been given away in the figure underneath and is coming just about to be 800 volts.

The 3-phase output potential and current waveform of inverter has been given away and it has been set up that there is significant amount of distortion in the potential output. The RMS ((Root Mean Square) value of powers (active and reactive) has also been noticed.

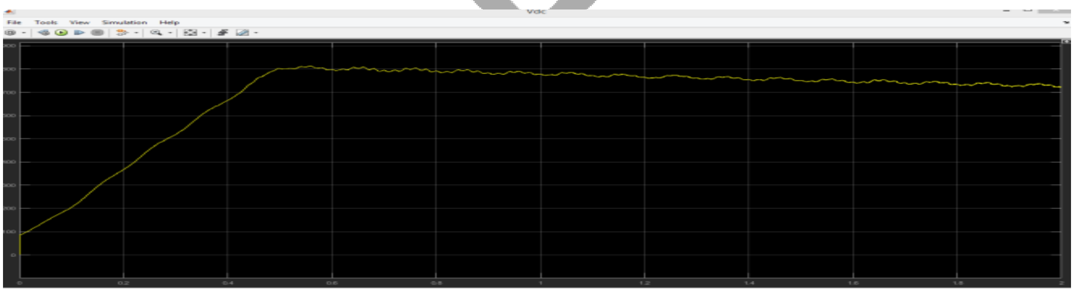

Figure: 16- Input DC Potential to Inverter

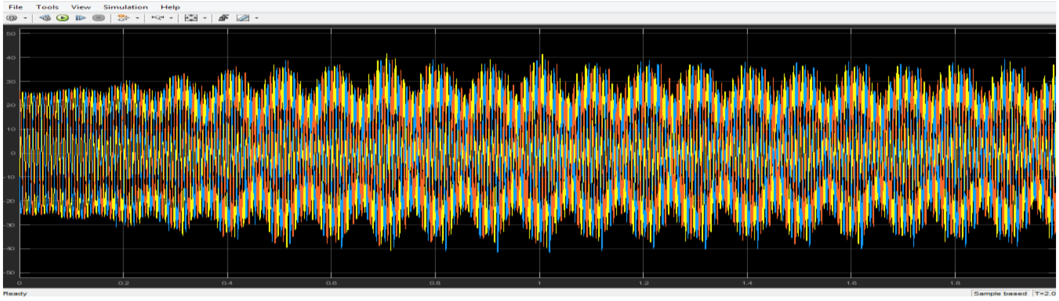

Figure: 17- Potential Output from Inverter with Pulse Modulation

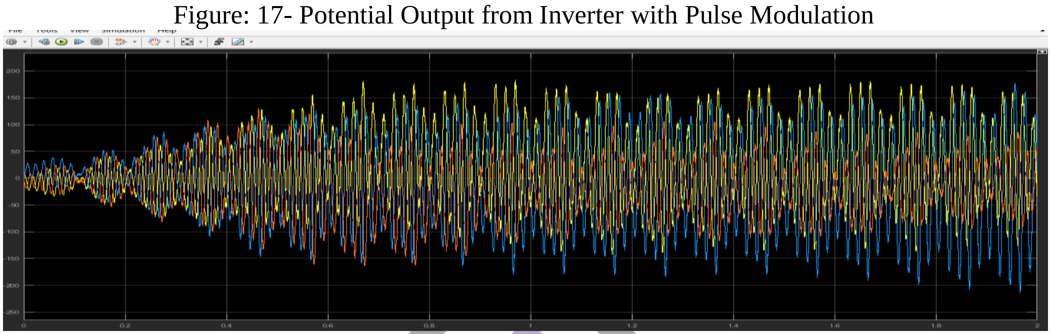

Figure: 18- Current Output from Inverter with Pulse Modulation

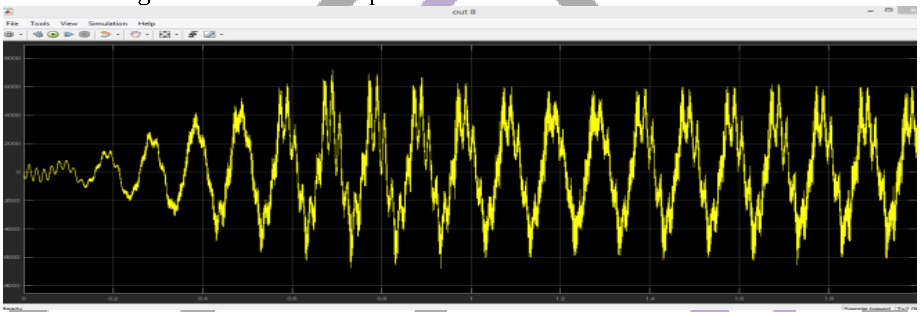

Figure: 19- Output of Active Power from Inverter with Pulse Modulation

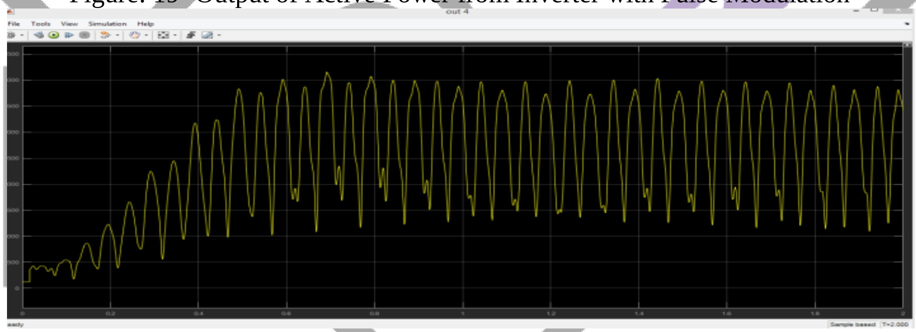

Figure: 20- Active Power Output RMS Value from Inverter with Pulse Modulation

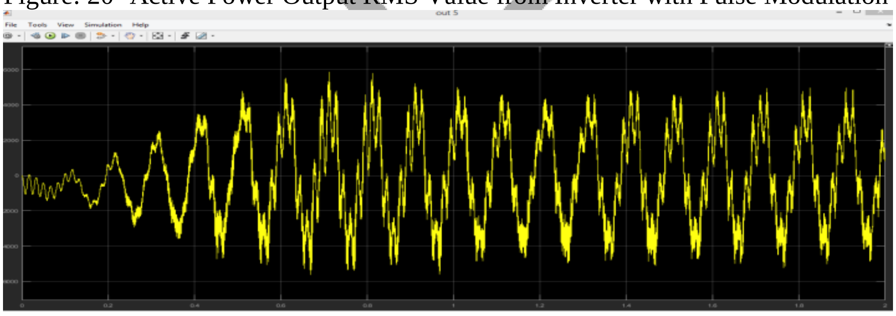

Figure: 21- Output of Reactive Power from Inverter with Pulse Modulation

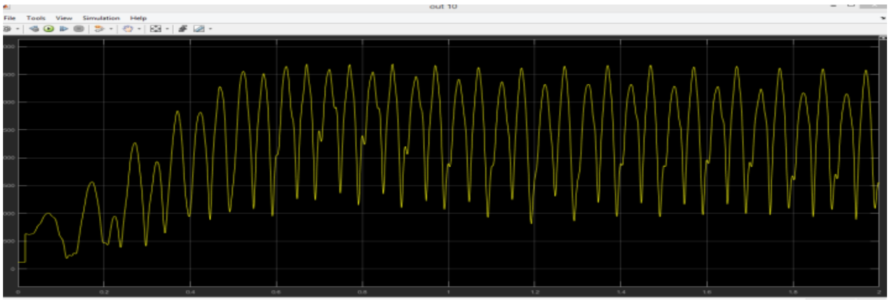

Figure: 22- Reactive Power Output RMS Value from Inverter with Pulse Modulation

***Case 2:* System Modeled With Vector Modulation**

Hybrid energy system (Solar and wind) with SC (Super Capacitor) has been demonstrated by means of space vector modulation to generate 6-pulses for the 3-bridge inverter.

The input DC (Direct Current) potential to the inverter which is being modeled with PM (Pulse Modulation) has been shown in the figure underneath and is coming just about to be 800 Volts,. This potential when fed to inverter is more stable as compared to DC (Direct Current) potential in case of PWM (Pulse Width Modulation) control.

The 3-phase output potential and current wave-form of the inverter has been shown and it has been set up that there is very smaller amount of distortion in potential output and wave-form is fairly smooth and incessant. The RMS (Root Mean Square) value of power (Active and Reactive) has also been noticed for further comparative investigation of consequences.

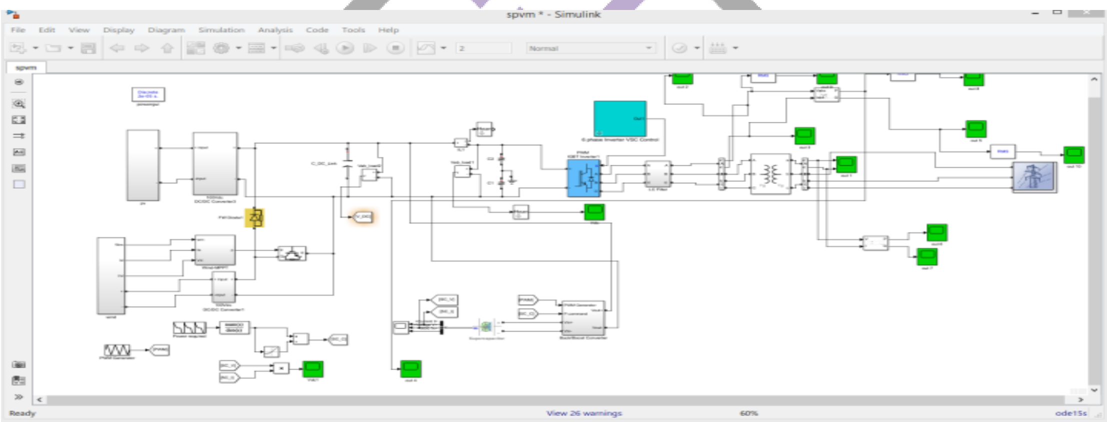

Figure: 23- System Exemplary With Vector Modulation

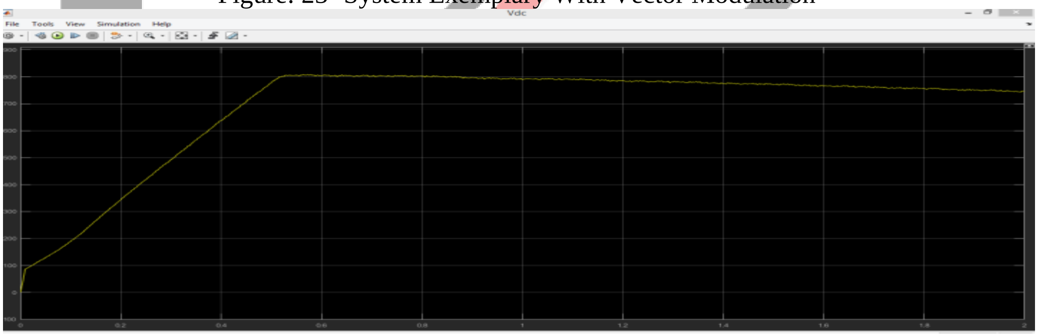

Figure: 24- Direct Current Potential Input to Inverter

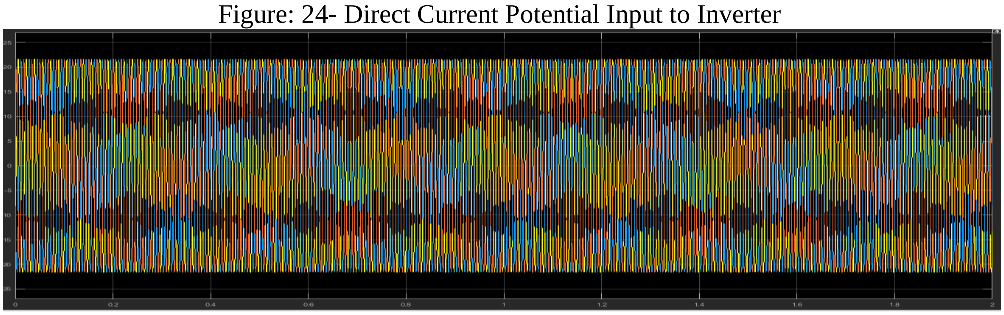

Figure: 25- Voltage Output from Inverter with Vector Modulation

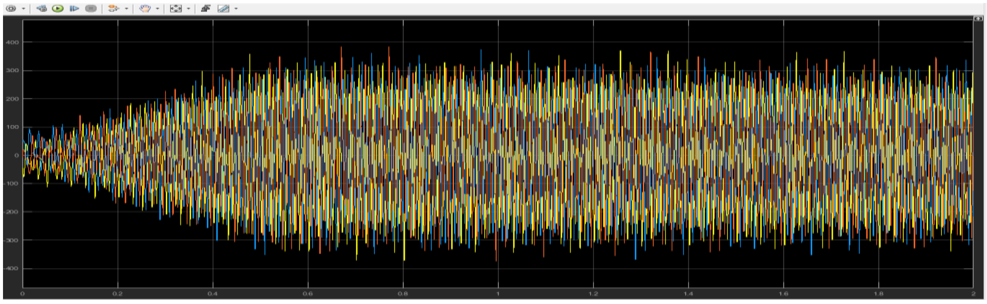

Figure: 26- Current Output from Inverter with Vector Modulation

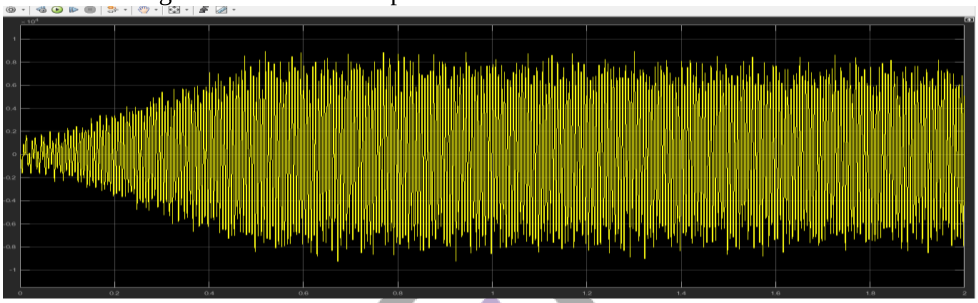

Figure: 27- Active Power Output from Inverter with Vector Modulation

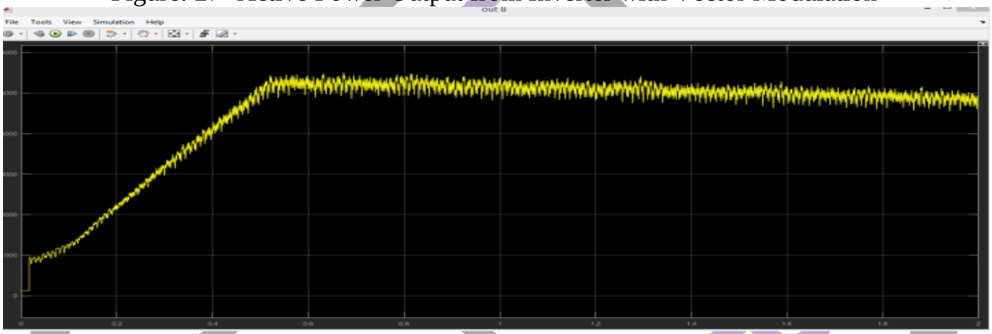

Figure: 28- RMS Value of Active Power Output from Inverter with Vector Modulation

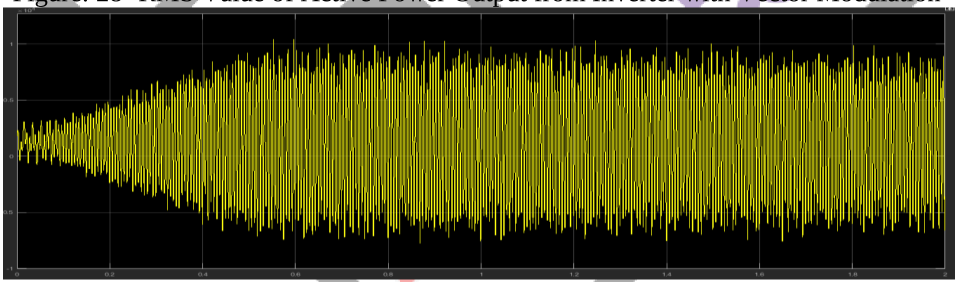

Figure: 29- Reactive Power Output from Inverter with Vector Modulation

Figure: 30- RMS Value of Reactive Power Output from Inverter with Vector Modulation

Outputs Being Fed To Grid

The grid energy schemes have been exemplary having 2 synchronous machines with their individual regulator's and exciters. Also there are 2 potential sources which Phase-to-phase potential of 230 Kilo-Volts and frequency 50-Hertz.

Table: 3- Grid System Parameters

Synchronous Machine	
Number of Machines	Two
Nominal Power	400 MVA
Line-to-Line Potential	20 KV
Frequency	50 Hertz
Transformers	
Winding-1 voltage	20 KV
Winding-2 voltage	230 KV
Nominal Power	400 MVA
Frequency	50 Hertz
3-Phase Voltage Source	
Phase-to-Phase Voltage	230 KV
Source Inductance	16.58×10^{-3} H
Source Resistance	0.0001 Ω

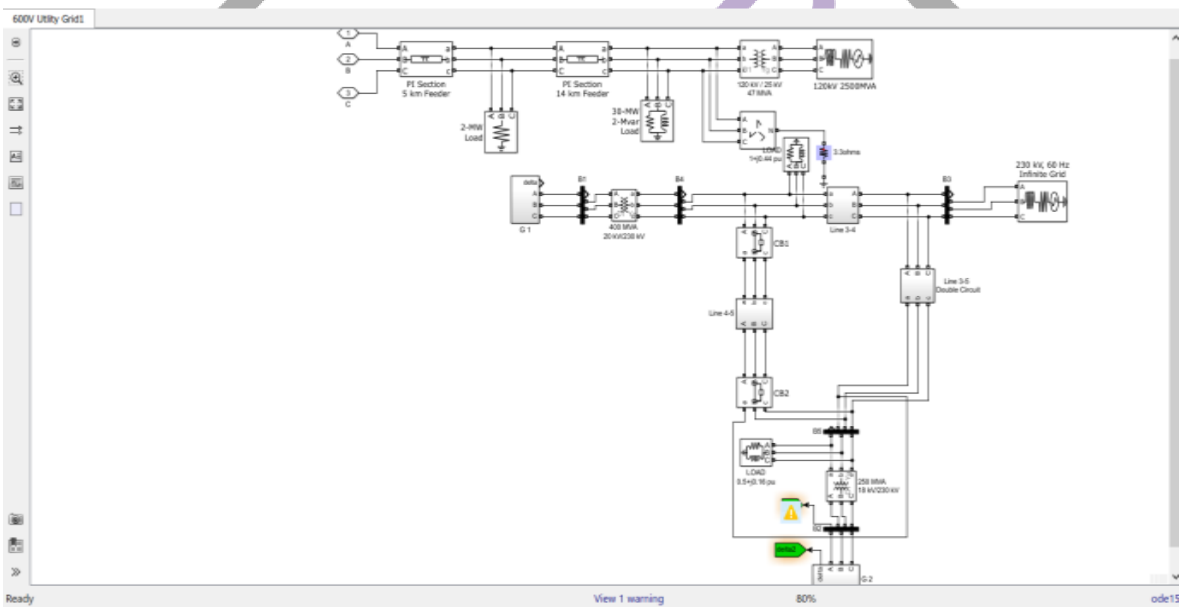

Figure: 31- Exemplary Grid System

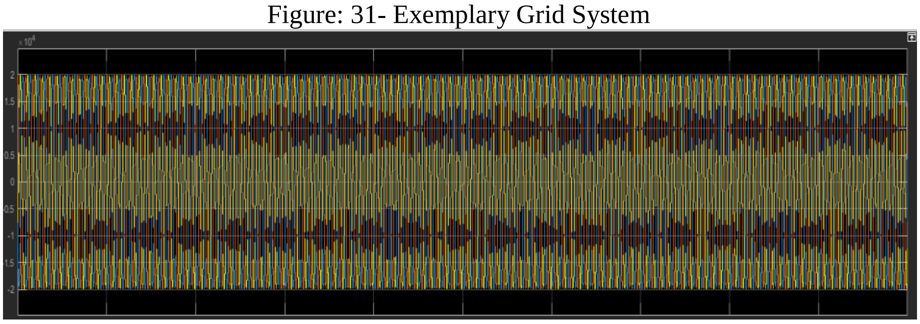

Figure: 32- Voltage Output being Fed to Grid

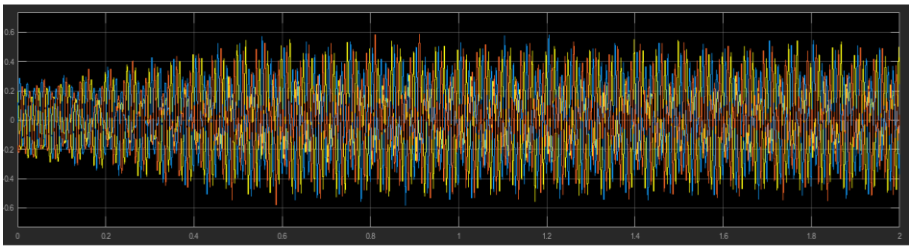

Figure: 33- Current Output being Fed to Grid

Validation

The assessment of an AC (Alternating Current) potential is constantly switching from zero ("0") up to +ive crest, over and done with zero to the -ive crest and back to zero once again. The RMS (Root Means Square) value is the Effective-value of a changing potential or current. It is the comparative constant Direct Current (steady) value which gives an analogous impact. Hence the RMS (Root Means Square) value of any electrical parameter can be used as a relative study of numerous outputs from a scheme. Here we have compared the RMS (Root Means Square) value of power (reactive power and active power) from the two systems.

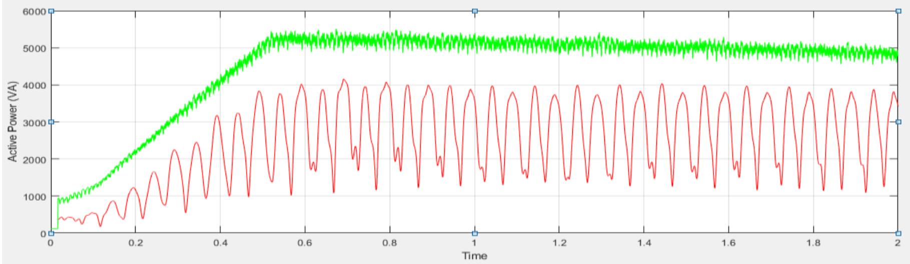

Figure: 34- Comparison of RMS Value of Real Power Output with Vector Modulation and Without Vector Modulation

As shown in graphs above the magnitude of real power output is superior from the scheme having inverter with vector modulation control as compared to scheme having inverter with simple PM (Pulse Modulation) control.

Also it can be resolved that the RMS (Root Means Square) value of the real power in inverter having PM (Pulse Modulation) is extremely pulsating between 1000 VA and 4000 VA. Although in case of inverter having vector modulation control the RMS (Root Means Square) value is just about DC signal at 5000 Volt-Ampere and a smaller amount pulsating then other graph.

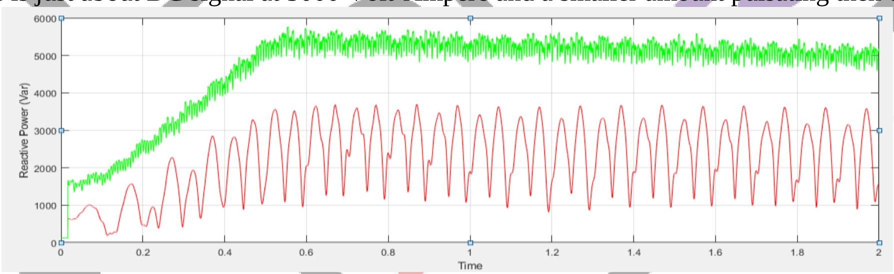

Figure: 35- Comparison of RMS Value of Reactive Power Output with Vector Modulation and Without Vector Modulation

Correspondingly The RMS (Root Means Square) value of the reactive power in scheme having vector modulation is superior as compared to the RMS (Root Means Square) value of reactive power in scheme having PM (Pulse Modulation). It can as well be seen that the disparity in the reactive power is more with PM (Pulse Modulation) control as compared to vector modulation. Henceforth it can be decided that if scheme is modeled with inverter having that modulation control output wave-form have more stable output which is too superior in magnitude as compared to simple PM (Pulse Modulation) control.

Hereafter by means of vector modulation control though modeling hybrid solar-wind energy scheme along with SC (Super Capacitor) control which is finally integrated with grid is a superior option.

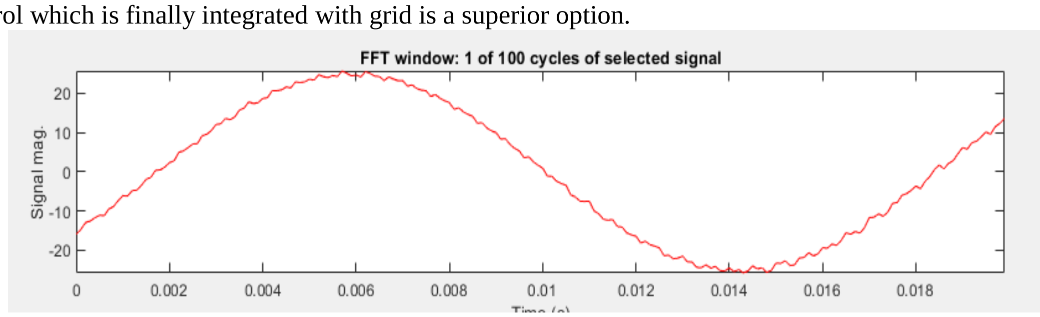

Figure: 36- FFT Analysis of Potential Output from Inverter with Pulse Modulation

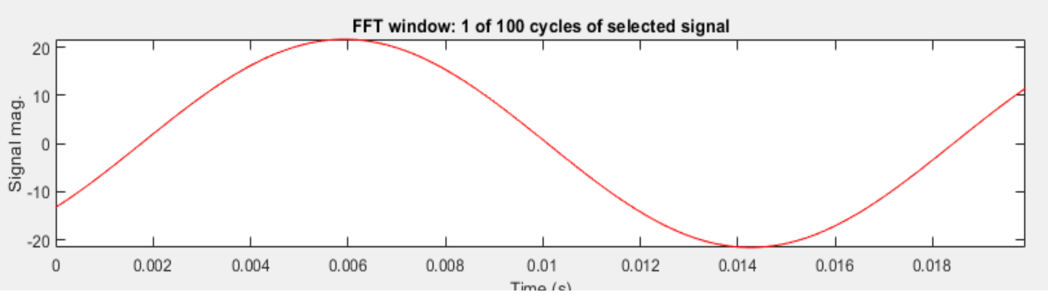

Figure: 37- FFT Analysis of Voltage Output from Inverter with Vector Modulation

With the purpose of see distortion in one cycle of potential wave-form output from inverter FFT analysis of potential output is done. It can be decided from the above FFT Windows that potential output from inverter with PM (Pulse Modulation) is having more distortion as compared to potential output from inverter having vector modulation control. Again it is concluded from the output waveform of the inverter that vector modulation is better control than simple pulse with modulation.

CONCLUSION

This research work delivers an ample design and carrying out of three-level Universal Bridge Inverter in a hybrid Photovoltaic Wind Energy scheme coupled with a SC (Super Capacitor) exemplary. The Inverter has been provided with suggested (SVMT) Space Vector Modulation Technique though integrating it with grid.

The basic notion about SVPWM for 3-legged VSI (Voltage Source Inverter) was conferred in detail. It is demonstrated how the potential or voltage space vectors are well-defined in a 3-dimensional (3-D) plane for a cascaded H-bridge multilevel inverter. The comparative study of the suggested method in a hybrid SC (Super Capacitor) based exemplary displays its effectiveness and an effectual choice for operation of grid integrated inverters.

The subsequent main decisive points were drawn through the analysis of scheme in the MATLAB/SIMULINK environment.

- The magnitude of real power output is superior from scheme having inverter with vector modulation control as compared to scheme having inverter with simple PM (Pulse Modulation) control. Even though calculating RMS (Root Means Square) value of real power it was set up to are just about 5000 Volt-Ampere and a lesser amount of pulsating than that of power output from inverter having PM (Pulse Modulation) Control.
- As well the RMS (Root Means Square) value of reactive power in scheme having vector modulation is superior as compared to the RMS (Root Means Square) value of reactive power in scheme having PM (Pulse Modulation) in magnitude along with in stability.
- The potential output of scheme from being fed to inverter for Direct Current-to-Alternating Current conversion. The FFT study of output potential wave-form approves that potential output from inverter having suggested SVMT (Space Vector Modulation Technique) is a lesser amount of distorted than that of PM (Pulse Modulation) Technique.
- The computational approach of the suggested modulation system is very easy and the method can be applied to multilevel inverter with any number of levels.

The scheme enactment has been boosted by advance integrating the scheme with SC (Super Capacitor) Exemplary that would compensate for changes in power demand of scheme.

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