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Performance Evaluation of A Developed Variable Frequency Drive: For Speed Control of Asynchronous Machines Use as Induction Generators.

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Abstract

This paper presents the performance characteristics of a developed variable frequency drive (VFD) adaptable for operation of ac machines speed control. The VFD developed is robust, durable, cheap and have low maintenance cost compared to conventional VFDs. The controlled asynchronous ac motor was operated to drive another self - excited induction motor (SEIM) at hyper synchronous speed to generate electricity, a phenomenon of the non constant - speed obtainable in hydro schemes. The drive converts input ac mains to dc followed by dc to ac conversion at any desired frequency from 20HZ-65HZ in this case. A diode full-wave bridge rectifier is used to effect ac to dc conversion, while MOSFET inverter is used to convert the dc to ac. An SG3524 voltage pulse width modulation IC was used to produce the gate pulses required to drive the MOSFET inverter. Digital display of the VFD's output voltage and frequency was actualised by means of the common anode seven segment displays by ICL7107 which is a three and half digit analogue to digital converter. The desired speed control is achieved by varying the frequency of the voltage supplied to the motor. The model tested on load was found to work satisfactorily with its operational characteristics.

Keywords: Variable Frequency Drive, Desired Frequency, Speed, Flux, Voltage, Current, Torque Control, PWM Inverter.

Nomenclature

A/D = Analogue to Digital
CCR = Current Control Inverter
EMF = Electromotive Force
IC = Integrated Circuit
IG = Induction Generator
IGBT = Insulated Gate Bipolar Transistor
MOSFET = Metallic Oxide Semiconductor Field Effect Transistor
$MRAS_S$ = Model Reference Adaptive Schemes
PE = Persistent Excitation
PM = Prime Mover
PWM = Pulse-Width-Modulation
SEIG = Self-Excited Induction Generator
VDF = Variable Frequency Drive

List of symbols

$\frac{dw_f}{dt} =$ instantaneous energy stored in the coupling field

Φ_{max} = magnetic flux density, weber

$\omega_2 = \omega_1 - \omega_r$ = the slip angular speed, rpm

ω_r = the (electrical) rotor speed, rpm

ω_1 = the stator magnetic field frequency, Hz

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E = the supply voltage, volts
E_b = back induced electromagnetic force, volts
f, f_o = supply frequency, and output frequency respectively, Hz
K_d = armature winding distribution factor
K_p = armature coil-pitch factor
L_m = the magnetizing (mutual) inductance, henrys
L_r = the rotor inductance, henrys
L_s = the stator inductance, henrys
N = number of turns per phase
n, x = refer to the initial or nominal load condition(n) and new load condition(x) respectively
Nsyn = rotational speed or synchronous speed, rpm
P = number of poles
P_e = instantaneous electrical power output, Kw
P_m = instantaneous mechanical input power, horse power
R_r or R_c= the rotor resistance, ohms
R_s = the stator resistance, ohms
S = slip
T = torque, N-m

1. Introduction:

Most process lines and industrial applications require speed variation ranging from low speed to very high speed. In accomplishing this alternating current (ac) machines are used in conjunction with controllers' which changes both the input and output signals to the electromagnetic devices to achieve the speed variation. Very accurate method of control entails the use of measured "parametric values" under normal and transient state conditions in the synchronously rotating reference frame [1]. In the application of very cheap, robust, durable, easily available and low maintenance asynchronous machines which do not requires external source of mains for its excitation in Pico/micro/mini hydro schemes for generation of quality and sustainable electricity for end users. The non constant steam/river flow has to be monitored and controlled to attain the required electromagnetic torque that can induce the desired electromagnetic force in the series connected conductors per phase in the armature windings. The applications of asynchronous machine as induction motor, induction generator and clutch and brake device depend on its slip speed or frequency. The power output of the induction generator must be monitored in line with the load demand, so that generator output voltage does not collapse to zero and de-energize the rotor residual magnetism. To guide against frequent excitation mostly in odd hour of operation of hydro schemes, speed controller of this nature becomes very important. Many papers were reviewed that gave us the background for this study:

In [2] the authors in theoretical study of a method for improved stator flux oriented control of the induction motor at very low rotor speeds, the flux estimation uses information extracted from the fundamental frequency component; no additional harmonic injection is necessary, through direct voltage integration is replaced by a full state observer to alleviate problems such as integrator bias. In this study complete standstill with full torque is not achievable, simulation show stable operation at arbitrary low rotor speeds, provided that the inductance is known with fairly high accuracy. The work revealed that use of no flux, no rotor speed, or position sensor and that no saliency exist, i.e a standard rotor is used in order to achieve stator flux orientation which replace rotor flux orientation in principle have the following shortcoming; they tend to fail at low rotor speeds, since the control strategy is based on flux estimation through direct integration of the stator voltages; also being known as the "voltage model". This method is therefore extremely sensitive at low speeds to variation of the stator resistance. From stimulation the speed estimation error would be dependent only on the rotor time constant error. In [3, 4, 5, 6, 7, 8] the authors suggested three ways of improving the low-speed performance (also for rotor flux orientation) to include;

(i) Improved flux estimation, by a proper selection of the observer gain, the flux observer can be made to behave as the "current" or "voltage" models, or anything in between. This is therefore a very general method, and has the benefit of being well researched and understood by control engineers,

(ii) Machine parameter estimation [9], and

(iii) Rotor speed and / or position estimation.

The electric circuit of an induction machine under steady state and transient state conditions has two inputs and outputs variables, the d and q direction stator voltages and currents, while the associated electric torque (per pole pair) is given by[1]:

$$T_m = I_M \left\{ \overline{\Psi} * \bar{i}_s \right\} \tag{1}$$

$$\frac{d\overline{\Psi}_s(t)}{dt} = -R_S \bar{i}_{s(}(t) - j\omega_1 \overline{\Psi}_s(t) + \bar{v}_s(t) \tag{2}$$

$$\frac{d\overline{\Psi}_r(t)}{dt} = -R_r \bar{i}_r(t) - j\omega_2 \overline{\Psi}_s(t) \tag{3}$$

And the well-known complex-variable IM model expressed in the synchronously reference frame natural to use with discrete-time estimation and control is:
Where,

$\bar{v}_s = v_{sd} + jv_{sq}$ = the applied stator voltage space phasor.

$\bar{i}_s = i_{sd} + ji_{sq}$, $\bar{i}_r = i_{rd} + i_{rq}$, and $\overline{\Psi}_s = \Psi_{sd} + j\Psi_{sq} = L_s\bar{i}_s + L_m\bar{i}_r$, $\overline{\Psi}_r = \psi_{rd} + j\Psi_{rq} = L_m\bar{i}_s + L_r\bar{i}_r$

are the stator and rotor current and flux linkage space phasors, respectively,

If the estimated flux differs from the true flux, the actual torque will differ from the desiire. Only the fundamental frequency component is used as information source hence at most two parameters can be estimated. In [10], the authors revealed the following;

(i) That the identification method for stator resistance is derived from the steady state equations of induction motor dynamics, and

(ii) That the identification method for rotor resistance is based on the linearly perturbed equations of induction motor dynamics about the operating point.

These methods use only the information of stator voltages and currents, and provides fairly good identification accuracy regardless of good conditions and be easily incorporated into any sensor less speed controller. The various control methods for the speed control of induction motors in the works of [10, 11, 12, 13] without rotational transducers are better than the conventional variable-voltage variable frequency inverter, but require accurate information of motor parameters like stator resistance R_s and rotor resistance R_r. Since these parameters vary with motor temperature, and their large variations can seriously degrade control performance of the recently proposed control methods, works reviewed by [10] showed that online identification of motor parameters need motor speed information and, hence, cannot be used for induction motors control with out rotational transducers. To overcome the difficulties in determining the machine parameters ($R_{s,}$ R_r) without both motor speed information, and rotational transducers, in the works of [14, 15] special techniques such as the use of ripples caused by a pulse width modulation was adopted, while injection of an additional frequency component was adopted in [16, 17]. These techniques are effective, but in [15], the high- order time derivatives of measured quantities and the accurate identification of the motor parameters are not guaranteed. In [14], the method requires high-grade sensor and fast analogue/digital (A/D) converter in order to detect high- frequency ripples (15≈20 KHz) to the desired accuracy, and furthermore, involves pure integration of some quantities; pure integration is sensitive to dc offset in measurement data. The neither pure integration nor differentiation of measured quantities required and adopted in full-order model reference adaptive schemes ($MRAS_S$) proposed in [16, 17] to identify the machine parameters worked in most operating conditions, but not necessarily in the generation mode. In [18], the authors maintained that an induction machine is largely inductive, and so, its currents have a saw tooth waveform with an average switching frequency determined by the segment with the lowest di/dt. Ideally, the current ripple can be made arbitrarily low by increasing the switching frequency limited by losses in the lower devices, thus, a good current control algorithm minimizes the switching frequency for a given ripple current. Most recent work on high performance ac drives are based on field-orientated or vector control, like the inner loop/inverter combination know as a current-controlled inverter (CCI), with the outer loop operating on position, velocity, or torque error to give a desired value of current and an inner loop giving control of the inverter. In this respect CCI control strategies are classified using [19, 20]:

(i) Ramp – comparison (PI controller); used for low-speed operation,
(ii) Predictive control; solves the machine equation(1) in real time, and
(iii) Hysteresis; used only for high-speed operation, has a major advantage in the simplicity of its hardware.

Most papers [21, 22, 23] considered the design of a ramp- comparison scheme in the frequency domain, thus optimizing the response for small disturbances only. The use of more sophisticated processors described in [24, 25], identified two emanating problems to include; the dependence on machine parameters values and cost of processors. The method needs further development before the gain in performance will pay back the complexity of the system. The conventional hysteresis controllers, at low speed with no neutral connection; under the "switching line controller", is robust, offer easy implementation, and can be further improved and examined as stated in [18]. The inverter output voltage of this scheme can take seven possible values, each corresponding to a unique switching state, except for the zero voltage vectors. The voltage switches from one discrete value to another when the current error crosses a line in the complex planes. The hysteresis controller is characterized by the use of position feed back to displace the switching lines and thus limit the switching frequency. In this wise [18] suggested two areas of improvement;

(i) At low speed, there is little motor back emf to buck the inverter voltage, and
(ii) High switching frequencies are possible.
(iii) And Ways suggested to deal effectively with these problems include;
(iv) Using clocked comparators,
(v) Injected zero - sequence in the reference channel, and

(vi) Switching lines rotated relative to those used in hysteresis controllers.

The papers in recent work in VDF pointed out problems encountered in induction motor speed control. In [26], the authors remarked that the control of induction motors is relatively difficult compared to others kinds of motors, such as direct-current and synchronous motors. To solve this problem and achieving performance; the following control schemes have been proposed:

(i) Field-oriented control, in which torque and flux can be, separated [27], and

(ii) To overcome the coupling between torque and flux in field-oriented control, Feed-back linearization control [28] is used.

To acquire more accurate flux information, by the measured stator currents, stator voltages, and motor speed by the combined models of using current model for rotor fluxes in the low speed - region and voltage model for stator flux in the high - speed region [29], variation in the motor parameters during operation inevitably leads to flux estimation error. Thus the adaptive flux developed for the case of simultaneous variation of stator and rotor resistance [26] worked, only if the electric motor torque in the persistent excitation (PE) condition is satisfied. This study presents the development of a conventional variable frequency drive (VFD) adopted for controlling the rotational speed (among other parameters) of asynchronous machine operated as induction generator. The drive converts input mains ac to dc followed by dc to ac conversion at a limited range of desired frequency (20HZ-65HZ). By controlling the frequency of the voltage supplied to the motor [30] the corresponding electromotive force (EMF) is induced in the armature winding where bulk of the energy transfer takes place and speed controlled is achieved. The energy conversion which takes place in the use asynchronous machines given by the relation [31];

$$P_m = P_e + \frac{dw_f}{dt} \quad (4)$$

Like their dc counterparts they also control ac motor torque and horsepower. With the advancement in power electronic and micro processors in the 1980's, VFDs allowed the largest motors to have their speed controlled depending on their application. This has also reduced the cost and increased the reliability and functionality of VFDs, allowing for the use of lower maintenance ac induction motors in most variable speed applications [32].

II Asynchronous machine (AM) model

The designed and develod VFD for IM was realised using figures 1 & 2. The power source provides the regulated dc voltages for the different functional stages. The PWM generates gate pulses which drives the MOSFET inverter. The MOSFET inverter converts the dc voltage reaching it back to ac voltage which is stepped up to drive the AC induction motor. The frequency of the output voltage is given by [33]:

$$F_o = \frac{E_b}{4.44 K_d K_P \Phi_{max} N}, \text{ Hz} \quad (5)$$

From the inverter the voltage vector can be varied, by varying the oscillation frequency of the pulse-width modulation with a varistor, thus controlling the motor speed. The operating output voltage is sampled and fed back to the digital meter for display. The frequency to voltage converter converts the output frequency of the PWM IC to a proportional voltage which is also monitored using digital voltmeter with the aid of a toggle switch. We made use of "SG3524 and ICL7107 data sheets", 2005 to actualize this model [33, 34].

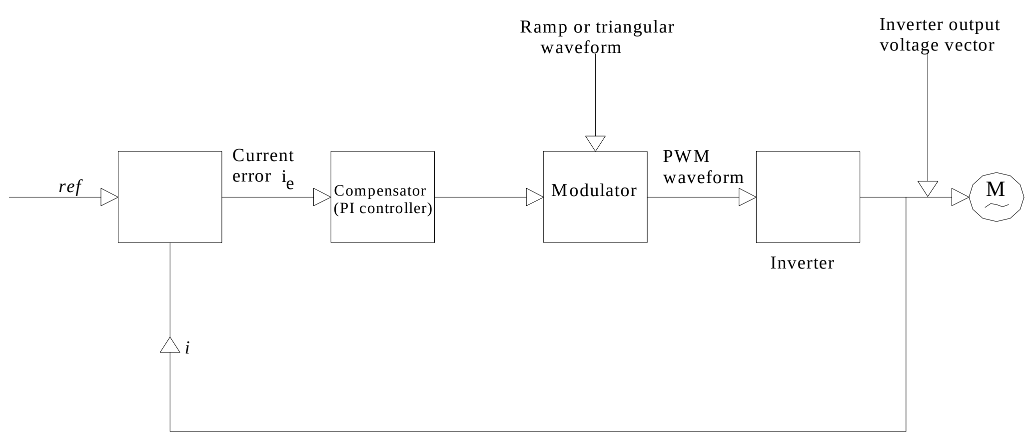

Fig.1 single line model of the variable frequency drive where each arm of the inverter is controlled independently.

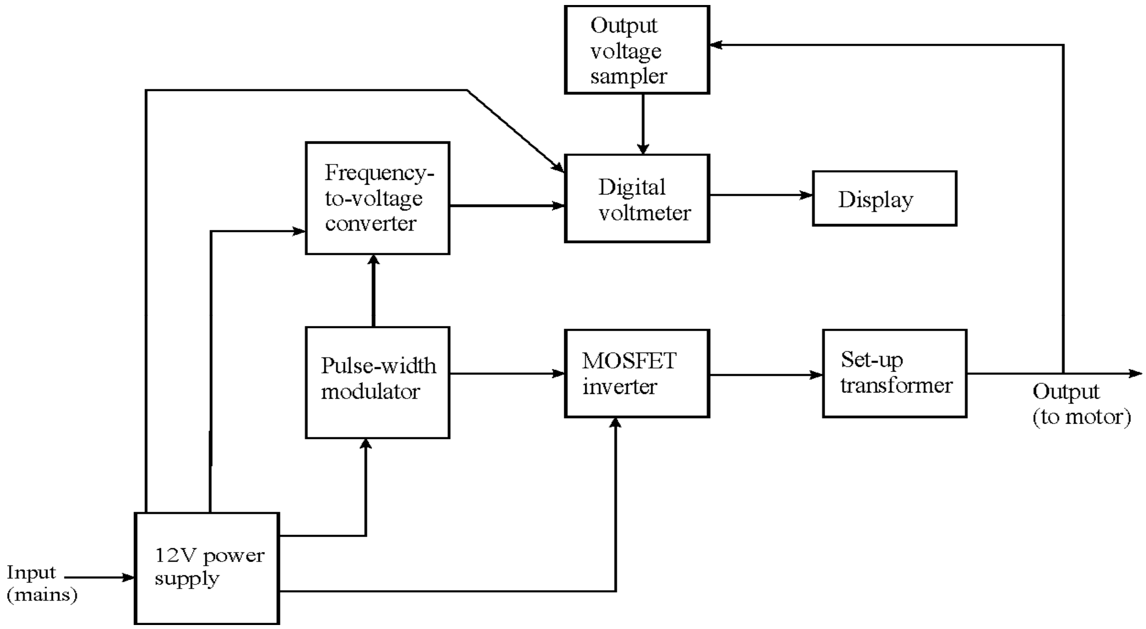

Fig. 2 block diagram of the variable frequency drive

III Principle of operation

The operation of the VFD is based on the principle that the synchronous speed of an ac motor is determine by the frequency of the ac supply voltage and the number of poles in the machine stator winding given by the relation [36]:

$$N_{syn} = \frac{120 f}{p}\text{, rpm} \qquad (5)$$

In the case of asynchronous machines the rotational speed of the motor is slightly less than the synchronous speed. In either case VFD can be used to adjust the rotational speed which has the advantage of reducing the effect the motor an inductive load has on the system's power factor by isolating the motor behind the dc bus. Another feature of the VFD is that it makes it possible for ac motor to be adapted for variable speed application and hence their use in place of dc motor since they are more robust, available, cheaper and lower to maintain. In effect, when we know the characteristics of a motor under a given load condition, we can determine its speed, torque, power, etc., under any other operating condition. These quantities are related by the equation [37]:

$$S_X = S_n\left[\frac{T_X}{T_n}\right]\left[\frac{R_X}{R_n}\right]\left[\frac{E_X}{E_n}\right]^2 \qquad 7$$

The only restriction to the application of equation (7) is that the new torque T_x must not be greater than $T_n\left[\frac{E_X}{E_n}\right]^2$, then the equation yields an accuracy better than 5%, which is sufficient for most practical problems. As soon as the driven motor or engine speed exceeds the synchronous speed the induction motor becomes a source of electricity, delivering active power to the electrical system to which it is connected. It is this type of machine that is called Asynchronous Induction Generator. The active power is directly proportional to the slip above synchronous speed and the rated output power is reached at very small slips, usually less than 3%. In this work the reactive power Q flows in the opposite direction to the active power P. To create the magnetic field capacitors were connected to the terminals of the armature windings as shown in figures 3a & b.

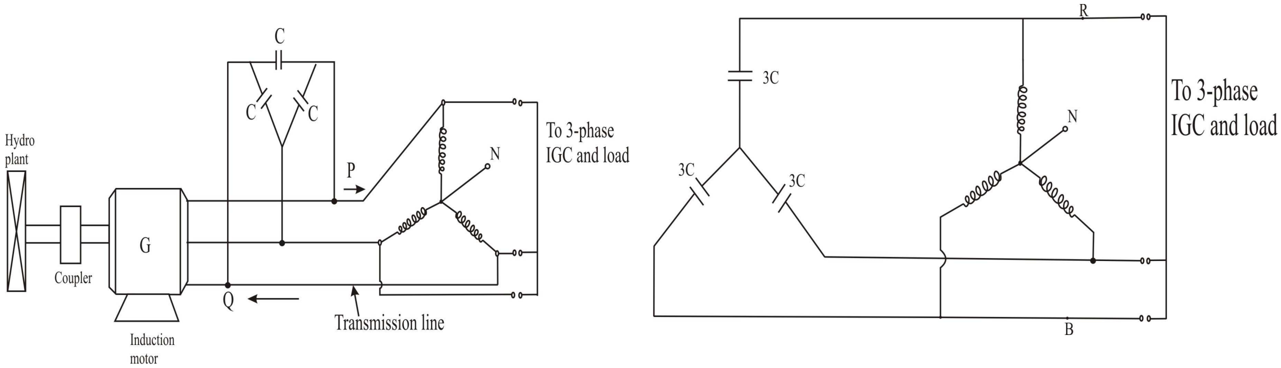

Fig. 3a Star-connected Induction Generators with star/delta-connected-excitation capacitors

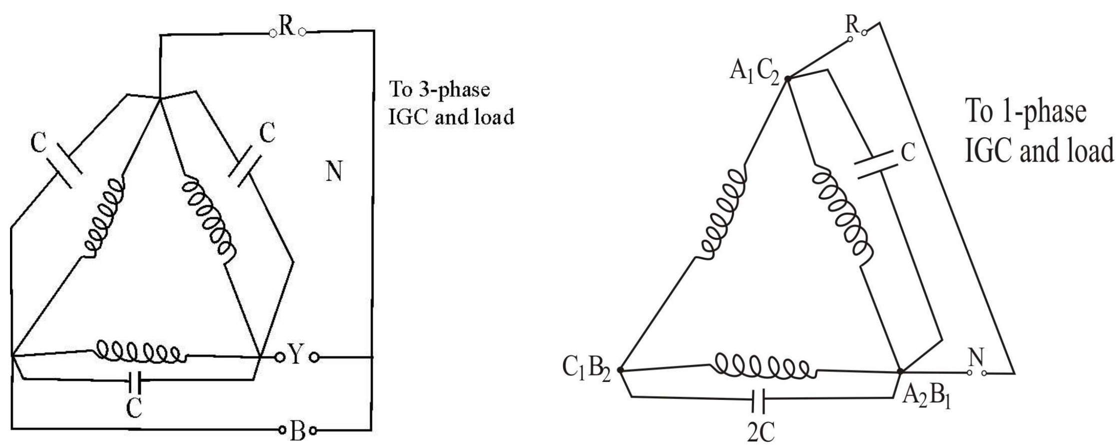

Fig. 3b Delta connected induction Generator with excitation capacitors

IV. Test results/ Interpretations

The measured output frequencies from the frequency to voltage convector compared with the frequencies from the pulse – width modulator to the converter showed differences of $\pm$ 1volts.

Figure 4 shows the relationship of frequency against motor rotor speed. The plot shows that whether it's the motor synchronous speed or the rotor speed it varies with the supply frequency which the work is set out to achieve for various speed control applications.

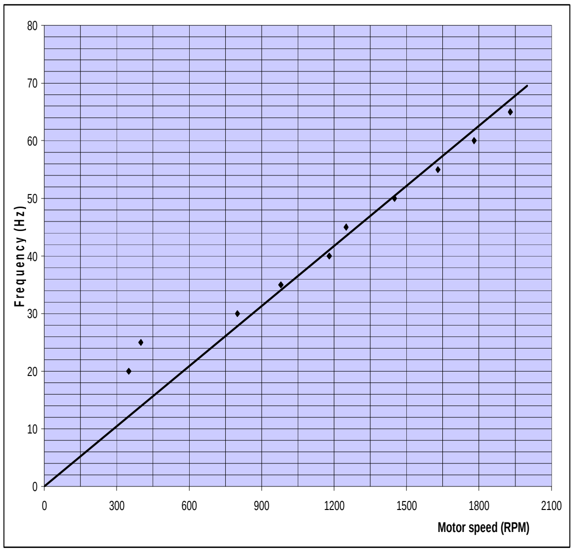

Fig.4 plot output frequency against motor rotor speed

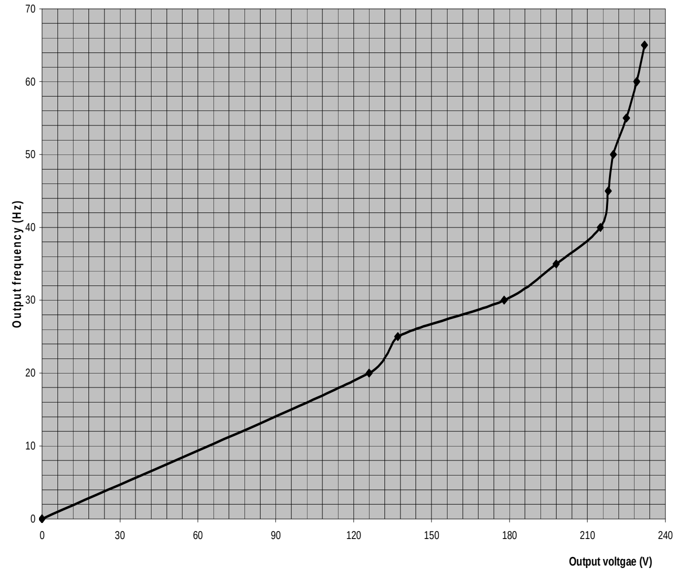

Fig.5 plot of output frequency against output voltage

The output frequency value a determining factor for the motor output torque which depends on the square of the voltage at the windings terminal is as shown in figure 5. The generated terminal voltages increases with the capacitance value, but it's limited by saturation of the iron as shown in figures 6 and 7, while Tables 1 and 2 present the readings taken during the experiment, from which inference can be drawn on the capability of VFD' application in generation of electricity using asynchronous machines [38]. The MOSFET gate input square pulses and the VFD output waveforms was satisfactory using oscilloscope.

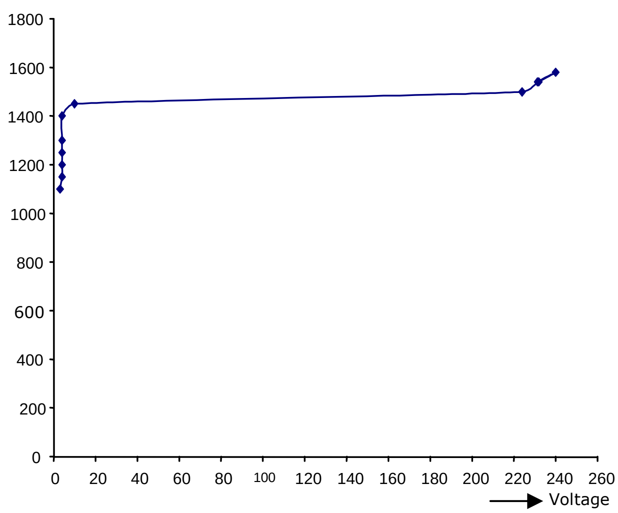

Fig. 6. Generated Voltage per Phase V_{bc} (Volts)

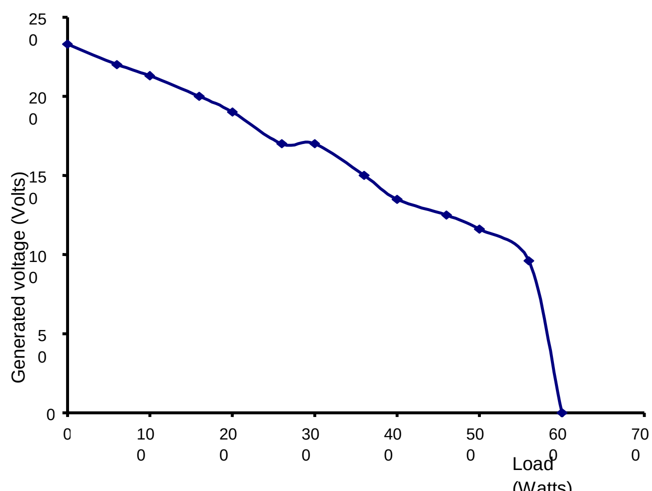

Fig. 7 Plot of Generated Voltage against Resistive Load

Table 1 Effect of Residual Magnetism on Induction Motor operated as Induction Generator with variable supply voltage at no-load

S/N	DC Supply Voltage (Volts)	Generator Speed Nr (Rpm)	Frequency of Generated Voltage (HZ)	Capacitance Value/Terminal Voltage		Type of Capacitor Connection	Full-Load Current (Amp)	Remark
				9.6µF	21.0µF			
				V_1 (volts)	V_2 (volts)			
1	50	400	No deflection	0.00	0.00	1C – 2C Arrangement	Induction Generator start rotating at 77 volts	
2	80	500	49.00	0.90	1.00			
3	100	900	49.00	10.40	11.20			
4	120	1300	49.00	133.00	148.00			
5	140	1350	49.00	145.40	162.70		60 Watts bulb connected glow, but voltage collapsed after losses.	
6	160	1400	49.00	160.00	174.00			

Table 2 Star connected SEIG parameter profile at no-load condition

Approximate value of shunt capacitor (µF)			Speed of PM (rpm)	Speed of IG (rpm)	Frequency (Hz)	Magnetizing current (Amp)			Generated voltage / phase, V_p (Volts)	Load current (Amp)	Value of load connected	Output power, P_o (watts)	Power factor	Input voltage (Volts)	Generated line voltage, V_L (Volts)
C1	C2	C3				Im_1	Im_2	Im_3							
20	20	20	1320	1200	45	1.25	1.25	1.25	192	0	0	0	1	75	332.60
			1380	1260	45	1.30	1.30	1.30	207	0	0	0	1	85	358.50
			1420	1300	45	1.40	1.40	1.40	216	0	0	0	1	95	374.10
			1440	1300	45	1.40	1.40	1.40	220	0	0	0	1	105	381.10
			1460	1310	45	1.42	1.42	1.42	222	0	0	0	1	115	384.50
			1460	1310	45	1.48	1.48	1.48	226	0	0	0	1	125	391.40
			1460	1310	45	1.50	1.50	1.50	230	0	0	0	1	135	398.40
			1480	1340	45	1.55	1.55	1.55	232	0	0	0	1	215	372.30
			1480	1340	45	1.55	1.55	1.55	233	0	0	0	1	225	403.60

V. Conclusion

The results and plots of the experimented model variable frequency drive have shown that as the frequency of the supply voltage reaching the asynchronous machines changes the rotational speed of the motor changes in direct proportionality by the VFD Linear relationship. This maintained constant volt per hertz ratio is the general rule in VFD control operation. By means of variable frequency drives, it's possible to adapt lower maintenance AC motors for variable speed applications applicable in hydro schemes electric energy generation with or without electronic speed regulator.

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