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Virtual Energy Storage: Converting an AC Drive to a Smart-Load

J. Carmona-Sanchez, M. Barnes, *Senior Member, IEEE* and J. Apsley, *Member, IEEE*

Abstract—This paper proposes a new Smart-Load concept using AC drives. The concept is based on a secondary control layer coordinated with the network and the load to provide active power support. The general Smart-Load concept is developed and synthesized for its practical implementation in network power–frequency support applications. A multi power–frequency droop line is proposed. The final idea is applied to a fan load powered by an AC drive based on an induction motor and a two level voltage source converter. Experimental results show that a full power–frequency response can be achieved by the Smart-Load within 2s of the network frequency deviation.

Index Terms— AC Drives, FPGA, Power–Frequency Support, Smart-Loads, Vector Control.

NOTATION

variables		subscripts	
f	Frequency (Hz)	g	generator
J	Inertia (kgm ²)	ge	generator electrical
k	Droop factor	gm	generator mechanical
η	Efficiency	m	motor
P	Power (W)	me	motor electrical
p	Pole pairs	mm	motor mechanical
T	Torque (Nm)	ms	motor stator
ω	Angular speed (rad/s)	n	network
		t	turbine
superscripts			
ref	Usual (no fault) operating condition	ss	Steady-state
		*	Desired value

I. INTRODUCTION

MANY network transients are related to active and reactive power imbalances [1][2]. When a power imbalance occurs this is reflected in network frequency deviations from nominal conditions. Under such circumstances, rotating masses of conventional synchronous generators release/ absorb the difference in energy to keep the system balance [3]. However, the replacement of conventional generation by low inertia renewable energy generation has resulted in the reduction of the fault level, stored energy and spare VA rating of the whole electric network, making the system more sensitive to frequency oscillations [4]. Research and development is focusing on the application of energy storage for the mitigation of such problems, however, the high cost of such devices is a hindrance to wide penetration of this

technology [5].

In electric power networks (EPNs), node voltages are kept within a small percentage of their nominal values. Hence, from the point of view of Demand–Side–Management (DSM), loads have usually fixed parameters such as impedance and power. Therefore, when the system is under severe contingency, DSM implies shedding of the load [3][6][7].

Some network frequency response mechanisms require a fast response (within seconds) from power reserves for network frequency support [8]. This could be easily covered by many types of load without significantly disturbing their driving process due to inherent presence of thermal or mechanical masses. Loads like heating, refrigerators, freezers and air conditioners are examples [9].

Reference [7] proposes a Smart–Load scheme based on voltage–dependant loads, such as heaters and lighting (e.g. LEDs). To achieve the Smart–Load, a voltage compensator is inserted in series between the supply and the load. By doing this, it is possible to control the voltage and active power of the load, hence contributing to network frequency support; additionally, it is possible to provide local voltage support but not both. Other developments for Smart–Loads focus on improving existing load shedding schemes, such as in [10], where noncritical loads are identified and shed at appropriate times in an industrial microgrid to prevent collapse of the system. In [11], GSM communication networks are used in combination with a Smart–Load management system (located at the consumer end) to limit the power flow to the consumer in case of a power shortage condition. Additionally, network frequency support can be achieved by averaging the power of the loads by switching them on/off with appropriate duty cycles [7].

The main loads in EPNs are motors, lighting and electric appliances. The load system is dominated by electric motors which cover about 60–70% of the total [12] [13]. The electric power network stability is largely impacted by the behaviour of these loads, making them potential candidates for DSM. However, loads driven by electric motors, such as air–conditioners, particularly those operated through AC drives, exhibit a constant active power over a wide network voltage and frequency range [14], which limits the possibility of continuous active power control [7]. Hence, until now research on this topic has remained untackled. This paper demonstrates that network power–frequency mitigation can be obtained from AC drives by the implementation of an advanced load management algorithm. A minimal upgrade of the AC drive control structure is necessary, thus, requiring only a small part of the investment and less hardware and less complexity than for energy storage devices.

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Furthermore, in addition to the technology/methods that allows converting an AC drive to an smart-load for network power-frequency support, there must be the right policies that incentivise consumers for taking part in supporting the grid. Regarding this matter, National Grid (UK) has created a framework called “Power Responsive” to be launched by 2020 [15]. This framework mainly focuses on the management of the demand side response (DSR) for network power-frequency support. This will be achieved by consumers reducing or increasing their demand as required. Under such a framework, consumers will receive financial incentives and lower their bills by intelligent use of energy. Additionally, the required standards need to be developed, or adapted, to set the guidelines to maximize the benefit of the variable power demand and response of the load to changing conditions of the network. This could be similar to the IEC 61850/61499 standards used for control and operation of distributed energy resources [16].

II. GENERAL SMART – LOAD CONCEPT BY USING AC DRIVES

The AC drive control structure is shown in Fig. 1, which also shows the power flow and system hardware. The AC drive control normally determines the inverter firing signals to set the electromagnetic torque (T_{me}) or mechanical speed of the motor (ω_{mm}). Smart load functionality would be achieved by the integration of a second outer control layer, which is similar to the control hierarchy already used in AC systems and microgrids. This secondary layer would be a supervisory control structure that could be activated under critical conditions of the system. The outer control structure would monitor the network variables (e.g. voltage, frequency), the load variables (e.g. speed, torque) or both, (Fig. 1), and adjust the desired motor speed or torque to adjust the active power drawn from the network. If an active rectifier is implemented on the AC drive’s network side, a certain amount of reactive power could be provided/absorbed by the AC drive and thus this could be used to provide local AC voltage support at the point of common coupling (PCC) between the network and the AC drive. This might be achieved by a droop control strategy. Due to cost and complexity, AC drives generally implement a passive full wave diode-bridge rectifier to convert the AC voltage to DC voltage. Hence, the following section concentrates only in the explanation of the network frequency support by AC drives.

Fig. 1. General AC drive implementation and AC drive Smart-Load concept.

III. ELECTROMECHANICAL DYNAMICS IN SYNCHRONOUS GENERATORS AND ELECTRIC MOTOR LOADS

In large EPNs, many synchronous generators are interconnected and all share the same network frequency. The frequency of the electrical network (f_n) is strongly dependent on the power balance between electrical sources and loads and the total system inertia [17]. Fig. 2 represents the electrical network, where, for simplicity, only a single generator and load are shown. The generator-network interface (GNI) is usually a connection transformer. The load-network interface (LNI) may be a soft starter [18], but for this work, only an AC drive will be considered.

The rate of change in mechanical speed (ω_{gm}) of a synchronous generator, with inertia J_{gm} (generator rotor plus turbine), as a function of the mechanical (P_{gm}) and electrical (P_{ge}) powers is governed by (1) [12][17]; where T_t is the turbine mechanical torque and T_{ge} is the generator electromagnetic torque. The actual electric power output (P_{ge_out}) delivered by the generator is given by (2), where η_g is the generator efficiency. The relation between the stator electric frequency (f_{ge}), stator electric angular speed (ω_{ge}) and the mechanical rotor angular speed is given by (3), where p_g represents the number of poles of the generator. This means that a change in generator speed directly changes the network frequency.

$$\omega_{gm} J_{gm} \frac{d\omega_{gm}}{dt} = \omega_{gm} T_t - \omega_{gm} T_{ge} \dots \dots \dots (1)$$

$$P_{ge_out} = \eta_g P_{ge} \dots \dots \dots (2)$$

$$f_{ge} = \frac{\omega_{ge}}{2\pi} = \frac{p_g}{4\pi} \omega_{gm} \dots \dots \dots (3)$$

Similarly, the rate of change in mechanical speed (ω_{mm}) of an electric induction motor (IM), with inertia J_{mm} (motor rotor plus load), as a function of the mechanical (P_{mm}) and electrical (P_{me}) power imbalances is governed by (4). In (4), T_l is the load mechanical torque, T_{me} is the motor electromagnetic torque. The relationship between the electric power required to drive the load and the actual input power (P_{me_in}) to the motor is governed by (5), where η_m is the motor efficiency. The relation between the IM stator electric angular speed (ω_{me}) and the mechanical rotor angular speed (ω_{mm}) is given by (6), where p_m represents the number of poles of the IM and (s) is the slip of the machine.

$$\omega_{mm} J_{mm} \frac{d\omega_{mm}}{dt} = \omega_{mm} T_{me} - \omega_{mm} T_l \dots \dots \dots (4)$$

$$P_{me} = \eta_m P_{me_in} \dots \dots \dots (5)$$

$$\omega_{me} = \frac{1}{(1-s)} \frac{p_m}{2} \omega_{mm} \dots \dots \dots (6)$$

Fig. 2. Synchronous generators and electric motors network connected.

In normal operation the rotor speed is set to match the requirements of the driven load and is not related to network frequency when operated by an AC drive. However changes in power drawn may indirectly affect the network frequency.

IV. NETWORK POWER-FREQUENCY SUPPORT BY AC DRIVES

A. Power-Frequency Droop Control for Synchronous Generators and for Electric Motor Loads

In EPNs, the rate of change of frequency depends on the system inertia and changes in power. To achieve a stable operation of the turbines in synchronous generators, the task of the turbine governor is to adjust the turbine speed. A power-frequency droop characteristic like the ones shown in Fig. 3a and mathematically represented by (7) is generally used, where f_n^{ref} and P_{ge}^{ref} refer to the frequency (50Hz or 60Hz) and active power references of the generating unit under normal operation conditions. f_n is the actual network frequency and P_{ge}^* is the desired active power when the network frequency deviates from its reference. The combination of many individual generation units contributes to keep the power-frequency droop factor within a small range (e.g. Fig.3a, slope k_{g12}). Such a characteristic defines the ability of the network to compensate for large power imbalances (by making use of spinning reserve) at the cost of small frequency deviations [12].

$$\Delta f_n = f_n^{ref} - f_n = -k_{pg} (P_{ge}^{ref} - P_{ge}^*) \dots \dots \dots (7)$$

Analogous to the power-frequency droop control in synchronous generators, a similar control can be implemented to AC drives to compensate for network frequency variations. However, in this case the power-frequency droop control must be in load mode (i.e. with a positive slope), Fig. 3b. This allows compatibility with synchronous generators droop control. From (5), the electric motor active power demand (P_{me_in}) can be manipulated by controlling the electric power being converted to mechanical power (P_{me}). Hence, considering a lossless power electronic interface the change in active power and network frequency relation for the power electronic interface, can be written as given by (8). Where, P_n^{ref} and $P_{me_in}^{ref}$ are the reference active powers for the AC

drive at the network side and for the electric motor, respectively, under normal operation and the (*) denotes the same terms when the network frequency deviates from its reference. From (8), a motor power reference command ($P_{me_in}^*$) can be generated for the participation of the motor under low network frequency, as given by (9).

$$f_n^{ref} - f_n = k_m (P_n^{ref} - P_n^*) \approx k_m (P_{me_in}^{ref} - P_{me_in}^*) \dots \dots \dots (8)$$

$$P_n^* = P_n^{ref} - \frac{f_n^{ref} - f_n}{k_m} \approx P_{me_in}^* \approx P_{me_in}^{ref} - \frac{f_n^{ref} - f_n}{k_m} \dots \dots \dots (9)$$

The implementation of the power-frequency droop line, in a multi motor-load system can be achieved by following similar procedures as those used for frequency droop control in a multi generator system, this is also shown in Fig. 3b.

B. Multi Power-Frequency Droop Line Approach

The droop line characteristic, shown in Fig. 3b, only considers the linear impact, of providing network frequency, on the motor input power (demand). The impact on the speed of the driven process (e.g. conveyors, fans, pumps, etc.) also needs to be considered. Therefore, it is desirable to be able to adjust the shape of the droop line considering the load profile as well as to minimize the impact of the network variations on the electric motor driven process. Hence, based on (9), a multi droop line piecewise linear approach is proposed that can be mathematically expressed as given by (10). Equation (10) states the combined effect of two droop factors k_{pm1} and k_{pm2} . Fig. 4 shows some examples. This equation has been per-unitized in terms of power. Hence, to obtain the desired motor power for network frequency support one has to multiply (10) by the power drawn by the motor in normal operating conditions, $P_{me_in}^{ref0}$, as given by (11). By using (11), the multi power-frequency droop characteristic can be set as desired as shown in Figs. 4a-c. Where $(f_n^{ref0}, P_{me_in}^{ref0})$ defines the transition from normal operation to frequency support, and the break points $(f_n^{ref1}, P_{me_in}^{ref1})$ and $(f_n^{ref2}, P_{me_in}^{ref2})$ define the transition from one droop factor to another.

$$k_m = 1 - \frac{(f_n^{ref0} - f_n^{ref1})(1 - p_1)}{f_n^{ref0} - f_n^{ref1}} - \frac{(f_n^{ref1} - f_n^{ref2})(p_1 - p_2)}{f_n^{ref1} - f_n^{ref2}} \dots \dots (10)$$

Fig. 3. Synchronous generators (a) and electric motors (b) desired droop characteristics.

Fig. 4. Power-frequency droop lines with two droop factors and their impact on the speed of square torque loads (fans and pumps) and constant torque loads.

$$P_{me_in}^* = P_{me_in}^{ref0} k_m \dots \dots \dots (11)$$

Proportionality indices p_1 and p_2 , and network frequency f_n^{01} and f_n^{12} values in (10) are defined by:

$$p_1 = \frac{P_{me_in}^{ref1}}{P_{me_in}^{ref0}}; P_{me_in}^{ref2} < P_{me_in}^{ref1} < P_{me_in}^{ref0} \dots \dots \dots (12)$$

$$p_2 = \frac{P_{me_in}^{ref2}}{P_{me_in}^{ref0}}; 0 < P_{me_in}^{ref2} < P_{me_in}^{ref1} \dots \dots \dots (13)$$

$$0 \leq p_2 \leq p_1 \leq 1 \dots \dots \dots (14)$$

$$f_n^{01} = f_n; f_n^{ref1} \leq f_n^{01} \leq f_n^{ref0} \dots \dots \dots (15)$$

$$f_n^{12} = f_n; f_n^{ref2} \leq f_n^{12} \leq f_n^{ref1} \dots \dots \dots (16)$$

$$f_n^{ref2} \leq f_n^{ref1} \leq f_n^{ref0} \dots \dots \dots (17)$$

Equation (11) is a general expression from which the desired motor power can be obtained according to a change in the network frequency and a reference power $P_{me_in}^{ref0}$. The droop factor k_m relates the proportion in power reduction to changes in the network frequency.

By knowing $P_{me_in}^{ref0}$ in advance, when implementing (10), the value of p_1 can be set by specifying the minimum desired power value, $P_{me_in}^{ref1}$, for the region defined by the droop gain k_{m1} . Better yet, since (10) has been per-unitized in terms of power, the value of p_1 can be arbitrarily set to have a value between 1 and p_2 , as defined by (14), without even knowing the value of $P_{me_in}^{ref0}$ or $P_{me_in}^{ref1}$ in advance. This is because the value of $P_{me_in}^{ref1}$ is a function of p_1 and $P_{me_in}^{ref0}$ as given by (12). By setting $p_1 = 0.4$, for example, one is indirectly defining $P_{me_in}^{ref1}$ to be 40 % of any given $P_{me_in}^{ref0}$. Similarly, p_2 can be arbitrarily set to have a value between p_1 and 0. Setting $p_2 = 0.2$, for example, indirectly defines $P_{me_in}^{ref2}$ to be 20 % of any given $P_{me_in}^{ref0}$.

Setting f_n^{ref0} , defines at what frequency threshold the power-frequency support must be triggered such that the AC drive will start reducing its power demand from $P_{me_in}^{ref0}$. Setting f_n^{ref1} , defines at what frequency threshold the rate of change of power support with respect to the network frequency will transition from that defined by k_{pm1} to that

defined by k_{pm2} . Setting f_n^{ref2} , defines at what frequency threshold the AC drive must be triggered for load shedding, see Fig. 5.

Values of frequency thresholds f_n^{ref0} , f_n^{ref1} and f_n^{ref2} are strongly dependant on the frequency of the network and on the frequency limits defined by the network operator. Setting these thresholds would be different for a 50Hz network than for a 60 Hz network. Section V of this paper gives an example for the UK electric network.

When implementing (10) and (11), the proportionality indices p_1 and p_2 and frequency thresholds f_n^{ref0} , f_n^{ref1} and f_n^{ref2} remain constant while f_n^{01} and f_n^{12} vary as the network frequency varies as stated by (15) and (16) respectively. Thus, the only variables in (10) are f_n^{01} and f_n^{12} . Furthermore, the last term in (10) is equal to zero until f_n^{12} reaches a value equal to or less than f_n^{ref1} . When f_n^{12} reaches a value equal to or less than f_n^{ref1} , the previous term in (10) is held constant by holding f_n^{01} equal to f_n^{ref1} while f_n^{12} is left to vary between f_n^{ref1} and f_n^{ref2} as the network frequency varies.

A further advantage of implementing (10) is that the multi-droop line characteristic can be modified online. The power variation with frequency drop can be adjusted as required by manipulating p_1 , p_2 , f_n^{ref0} , f_n^{ref1} or f_n^{ref2} in (10). Examples of this are given in Figs. 4a-c. Droop factors k_{pm1} and k_{pm2} are indirectly defined when setting p_1 , p_2 , f_n^{ref0} , f_n^{ref1} and f_n^{ref2} in (10).

C. General Control Structure for Network Power-Frequency Support by AC drives

The effect of reducing the load power depends on the torque-speed characteristic of the driven load. An example is shown in Figs. 4a-b for a pump or fan, and the proposed technique is also valid for constant torque loads, as shown in Fig. 4c, since in both cases, the input power reduces as the speed reduces [19]. It is not valid for constant power loads, where reducing the input power would prevent the load from operating.

Assuming a fixed machine efficiency, the relationship

$$P_{110}^* = P_{110}^{ref0} k_{110} = P_{110}^{ss} k_{110} = P_{110}^{ss} k_{110} \dots \dots \dots (18)$$
$$P_{me}^* = \omega_{mm} T_{me}^* \dots\dots\dots (19)$$

V. APPLICATION EXAMPLE 1 AND EXPERIMENTAL VALIDATION – FAN LOAD

$$P_{mm} = \omega_{mm} T_l = K_{fan} \omega_{mm}^3 \dots\dots\dots(20)$$

Figure 1 is a graph showing the relationship between System frequency [Hz] (Y-axis, ranging from 49.40 to 50.25) and Fan active power desired (% of full fan power) (X-axis, ranging from 0% to 100%).

The graph illustrates the frequency limits and fan load participation in high frequency response or in the normal operation region. Key features include:

- Frequency Limits:**
 - Upper National Grid Statutory Limit (50.50 Hz)
 - Upper National Grid Operational Limit (50.20 Hz)
 - Ideal Operational Point (50 Hz)
 - Lower National Grid Operational Limit (49.80 Hz)
 - Lower National Grid Statutory Limit (49.50 Hz)
- Operation Region:**
 - Normal operation region (above 49.80 Hz)
 - Fan load participation in primary and secondary response (below 49.80 Hz)
- Key Points and Parameters:**
 - Triggering point at 49.82 Hz
 - From 20% to 0% power (indicated by k_{m2})
 - IM is stopped at 49.52 Hz (indicated by k_{m1})
 - Reference power points: P^{ref}_0 , P^{ref}_1 , P^{ref}_2
 - Measured power points: P^{me}_0 , P^{me}_1 , P^{me}_2

Frequency Limits (Hz)			Proportionality indices (per unitized percentage of power limits needed for (10))	
f_n^{ref0}	f_n^{ref1}	f_n^{ref2}	p_1	p_2
49.82	49.75	49.52	0.4	0.2

- The UK's network frequency is nominally 50 Hz. The region delimited by the NG operational limits is considered the normal operating condition of the network. In the "high frequency response" region (above 50.20Hz), generation exceeds the demand. Increasing the power demand in this region would be a waste of energy, therefore, no load participation by the AC drive is considered above 50.20 Hz. 49.8 Hz is at the limit of normal network operation. Thus, all frequencies above 49.82 Hz are rejected for load power reduction. The network will benefit from the AC drive starting to reduce its power from 49.82Hz downwards. In the region defined by k_{m1} , the reduction in the AC drive - fan power is from 100% to 40% in proportion to the network frequency. This effect can be added to the *primary frequency response mechanism*. If we add the effect of many AC drives powering fan loads in the system, the result is more likely to be large enough to keep the system frequency at acceptable levels as discussed in section VI. In the region defined by k_{m2} , the rate of power reduction is less than in the first region. This is because most of the support wanted from the AC fan drive was delivered during the first seconds of the deviation of the network frequency from the operational limits. By the time the network frequency has reached 49.75 Hz, other control schemes to compensate for the deviation in the system frequency should have been activated, such as the *secondary frequency response mechanism*. However, there is still more room (from the AC drive - fan) to provide power support to the network in case the deviation of the system frequency is

beyond 49.75 Hz. By the time the system frequency has achieved a value of 49.52 Hz, the AC drive-fan has been stopped, since this might be an indication that something worse has happened in the network and there is no reason to keep the fan running at lower power. Therefore, 20% of the target active power consumed by the fan (in steady-state conditions) defines the latest operational point.

A. AC Fan Drive Hardware Configuration

The AC Drive and fan, used to prove the power-frequency concept, is shown in Fig. 7a. It consists of a SCHAFFNER NSG 1007-5 controllable variable three-phase voltage-frequency source rated at 300V–16A (phase rms) which can generate steps down and steps up in frequency with a resolution of 0.01 Hz. The three-phase AC to DC conversion is achieved by a SEMIKRON SKD100/16 diode bridge rectifier rated at 110A and 1.6kV (blocking voltage). The DC capacitors are rated at 450V DC, 2200 μ F ($\pm 20\%$), -40/+85°C. Polypropylene snubber capacitors are implemented to suppress transient voltages. A Mitsubishi PM150CL1A120 IGBT Intelligent Power Module (IPM) is used to invert the voltage from DC to AC, rated at 120kW, 150A, 800V DC. A 4.5 kHz switching frequency was used with 2 μ s dead time and sine-triangle PWM (SPWM). The IM is rated at 4 kW, 400 V rms line to line, 2850 RPM, two poles. It is directly coupled to a fully enclosed centrifugal fan (commercially

bought in packaged unit). Parameters of the IM and fan load are given in Table II, and further information on experimental characterisation can be found in [20].

B. AC Drive Vector Control Implementation

The main hardware control structure is shown in Fig. 7b-c. Line to line network voltages v_{abn} and v_{bcn} , IM stator currents i_{asIM} and i_{bsIM} and rotor speed are measured. A NI PXI-7851R card with integrated analogue and digital input/outputs with FPGA technology was employed for the control structure shown in Fig. 7b.

“Indirect rotor flux oriented control (IRFOC)” was used to provide high bandwidth control of torque, which in turn provides high bandwidth control of active power [25]. The control of the mechanical speed is achieved by a proportional integral controller (PI) acting on the speed error ($\omega_{mm}^* - \omega_{mm}$) which in turn generates the corresponding torque command. ω_{mm}^* would be generated by a slowly varying target speed reference ω_{mm}^{tar} (coming from a thermostat for example) and a slew rate limiter to ramp the IM rotor speed reference up/down. The torque command sent to the IRFOC is cascaded with a proportional integral current controller (not shown in Fig. 7b for simplicity). Damping factors and bandwidth used for the controllers are as given in Table III.

A slew rate limiter is configured to allow the reference for

Fig. 7. Test hardware: (a) AC drive hardware configuration, (b) AC drive vector control and (c) network power frequency droop control implementation.

the current PI controller ($i_{qs_af}^*$) to change by $50\mu A$ per $20\mu s$ (i.e. with a slope of $2.5 A/s$) under transient conditions; as an example if the desired stator current q component ($i_{qs_be}^*$) is switched from $2.5A$ to $0A$, the desired stator current q component $i_{qs_af}^*$ for the PI controller will be ramped from $2.5A$ to $0A$ and it will take $1s$ for $i_{qs_af}^*$ to be equal to $i_{qs_be}^*$. The output from the slew rate limiter ($i_{qs_af}^*$) is taken as the current reference for the PI controller.

C. Power-Frequency Droop Control Implementation

The network power-frequency support is achieved by the coordination of the power-frequency algorithm shown in Fig. 5 to modify the torque reference for the IRFOC of the IM as shown in Figs. 7b-c. The frequency limits and proportionality indices are as given in Table I. In this implementation, the network active power (P_n) is indirectly controlled by controlling P_{me} . However, in practice, motor and converter efficiency will vary with load, so the relationship will not be exactly linear. The steady-state load power value needed for P_{nm}^{ss} is calculated by substituting ω_{nm} for ω_{mm}^* in (20).

In Fig. 7c, the network frequency is estimated by implementing a Phase-Locked Loop (PLL) algorithm as shown in Fig. 8 [26-27]. Line to line voltages v_{abn} and v_{bcn} are transformed to the synchronous qd reference frame (where the q axis is leading the d axis by 90 degrees). The line to line network voltage magnitude (v_{ll}) is forced to align with the q axis by a proportional-integral controller (PI_{pll}) acting on the component error v_{dll} . The PI_{pll} controller produces an angular speed command ω_{pI} which is compensated by the nominal network angular speed ω_{pll0} (i.e. 50 Hz or 60 Hz) resulting in the estimation of the instantaneous network angular speed ω_{pll} (in rad/s) and frequency f_{pll} (in Hz). The loop is closed by the generation of the transformation angle θ_{abn} by the angle oscillator. PI_{pll} parameters are as given in Table IV.

The controllable voltage source produces pure sinusoidal voltages. However, the real voltages at the distribution side of a network are usually non ideal due to the effect of load-switching by other users, commutation by nearby power electronic equipment and the additional transient effects of lightning strikes and distribution faults [28]. Hence, to get a closer representation of the worst-case network voltage shape in the real world, the voltages used to estimate the network frequency, for the results shown in the next section, are the voltages at the input of the passive rectifier (as shown in Fig. 7); these voltages are a function of the network impedance and the non-linear current drawn by the passive rectifier, making the AC voltages distorted, see Fig. 9c.

Distorted voltages introduce noise in the frequency estimated by the PLL. Therefore, f_{pll} is smoothed through the slew-rate limiter shown in Fig. 7c. Filtering of the network voltages would be another possibility. However, the implementation of a slew rate limiter needs fewer FPGA resources than a low pass filter [20]. The rate limiter is configured to allow the measured frequency (f_{pll}) to change by $10\mu Hz$ per $20\mu s$ under transient conditions (i.e. with a slope of $0.5 Hz/s$). This ensures that if the network frequency

Fig. 8. PLL Implementation.

TABLE II: AC DRIVE PARAMETERS [20]

Network Impedance		DC Link Impedance	
$R_n=0.2\ \Omega$	$L_n=0.001585H$	$R_{dc}=3300\ \Omega\ (25W)$	$C_{dc}=2200\ \mu F$
Induction Machine Parameters			
R_s (stator resistance)= 1.61 Ω		L_r ' (rotor leakage-inductance) = 0.007 H	
R_r ' (rotor resistance)= 1.00 Ω		L_s (stator leakage-inductance) = 0.007 H	
L_m (magnetizing resistance) = 0.293 H			The superscript (‘) means quantity referred to the stator
J_{motor} (rotor moment of inertia) = 0.010 kgm ²			
Fan Parameters			
Nominal power = 4 kW		J_{fan} (moment of inertia)=0.7636 kgm ²	
Nominal speed = 2850 rpm		$K_{fan}=0.00012798\ Nms^2rad^{-2}$	

TABLE III: PI CURRENT AND SPEED CONTROL PARAMETERS [20]

Current Control Loops		Speed Control Loop	
ζ_i (damping factor)	1	ζ_s (damping factor)	0.8
ω_{ni} (bandwidth)	1571 rad/s	ω_{ns} (bandwidth)	0.247 rad/s

TABLE IV: PI PARAMETERS FOR THE PLL

$PI_{pll} = s^{-1}k_{ipll} + k_{ppll}$, $k_{ppll} = 2\zeta_{pll}\omega_{npll}$, $k_{ipll} = \omega_{npll}^2$	
ζ_{pll} (damping factor) = 1	ω_{npll} (bandwidth) = 2π rad/s

suddenly drops from 50 Hz to 49.5 Hz, the slew rate limiter output (f_{pll}^{fil}) will achieve this value (49.5 Hz), ideally, in $1s$. This is fast enough for the control to trigger the IM for low network frequency load shedding.

D. Experimental Results

Fig. 9 shows the start-up, acceleration to full speed and normal operation of the fan drive. Fig. 9a-b shows the speed and inner current control loops experimental results acquired by applying the IRFOC to the AC drive. The stator d current component reference (i_{ds}^*) was set to 3.6 Amps at $5s$ (Fig. 9b) and it was kept at this value during the full operation of the AC drive. As the magnetizing current is kept constant ($i_{mr} \approx i_{ds}$), the torque (T_{me}) is proportional to the stator i_{qs} current component [25]. At $10s$, the rotor speed reference was ramped up from 0 rad/s to 180 rad/s as shown in Fig. 9a. The speed PI controller provides the desired torque ($T_{elM_opI}^*$). As the rotor speed reference increases, the IM accelerates.

The IM currents are sampled, filtered and transformed to qd values at a rate of $330 kHz$. A first order low pass filter was programed in the FPGA with a bandwidth of half of the switching frequency in order to reject the switching effect due to the SPWM modulation and hence to extract the main component of the IM current. The resultant filtered current for the phase "a" is shown in Fig. 9g. Since a high bandwidth was employed for the filter, this did not have a significant impact on the closed loop control performance.

Fig. 9. Experimental results: (a) speed control, (b) current control loops response and steady state behavior (c-g) of the system shown in Fig. 7.

Fig. 9c-g shows the steady state behaviour of the AC drive. Converter switching can be observed as voltage spikes in the DC link voltage (v_{dc}). This effect also propagates to the network side of the AC drive. Notches in the line to line voltages of the network side v_{abn} and v_{bcn} can be observed. Although the effect of the stray inductance has been minimized with the addition of snubber capacitors, its effect cannot be suppressed completely. Currents at the network side (i_{an}) and DC side (i_{dc}) follow a characteristic shape for this type of topology, despite the presence of voltage spikes in the system. A full simulation and experimental benchmarking of this AC drive topology (Fig. 7a) can be found in [20].

Fig 10 shows the smart load response to step changes in system frequency; at 150.5s, the network frequency dropped from 50Hz to a value of 49.60 Hz, and at 172.5s the frequency was returned to 50Hz. Fig. 10a-b shows the network frequency estimation by the PLL (Fig. 8). Results show that, even with the use of a very small bandwidth, noise distortion of the voltage propagates to the PLL error, which in turn

impacts the estimation of the system frequency (f_{pll}) producing false estimations which varies from 47.5 Hz to 52.5 Hz. However, the implementation of a slew rate limiter helps to suppress false estimations of the system frequency and kept a better approximation (f_{pll}^{filt}) at the cost of a slower response. Nevertheless, this response is still fast enough for its consideration in the frequency primary response mechanism.

Fig. 10c shows the contribution of the AC drive active power to changes of the network frequency. At 151s, when the frequency at the output of the slew rate limiter (f_{pll}^{filt}), achieved 49.82 Hz, the control structure (Fig. 7c) generated a desired torque (T_{me}^*) corresponding to this frequency and it switched the control structure in Fig. 7b (by the use of the frequency support command) from speed closed loop control (ω_{mm}^*) to open loop torque control (T_{me}^*). As the speed control loop is opened, its PI controller output ($T_{elM_opI}^*$) saturates as shown in Fig. 10d. During low network frequency conditions, the open loop torque control reference (T_{me}^*) is produced from the actual rotor speed (ω_{mm}) and the desired active power (P_{me}^*) for the AC drive under low network frequency conditions ($f_n \leq 49.82$ Hz) as shown in Fig. 5. Changing from $T_{elM_opI}^*$ to T_{me}^* , directly impacts the desired torque current component ($i_{qs_be}^*$), Fig. 10e. However, these changes are smoothed by the slew rate current limiter shown in Fig. 7b.

As the torque reference (T_{me}^*) is decreased, the IM power is decreased (P_{me}) and the network power (P_n) is decreased as well, as can be seen in Fig. 10c. A full response is achieved in about 1.5s. This is fast enough for the IM fan load to participate in the “primary response” mechanism which requires a response within 10s and to sustain the drop in power for a further 20s. It can be observed in Fig. 10c that the IM active power remains at the desired power proportional to the system frequency, even under variations of the IM speed (ω_{mm} , Fig. 10i) and torque reference (T_{me}^*). Torque and speed change to adjust themselves to the desired power. Furthermore, there is not a rapid reduction in the rotor speed due to the spare energy stored in the system inertia being released to balance the power being drawn by the fan load.

The frequency of the network was kept at 49.60 Hz for 20s to analyse the performance of the system. The fan speed is gradually reduced from 180 rad/s (100%) to 130 rad/s (72%). The network active power drawn by the AC drive went from 900 Watts (100%) to 300 Watts (33%) instantaneously.

The worst case scenario for system recovery would be if the frequency suddenly increases from a very low value to the normal operation condition (50 Hz). This is because the IM fan load could be suddenly switched from the power-frequency control to the closed speed control and start to draw a very high power in a short period of time. Hence, at 172.5s the network is returned to its nominal frequency, 50Hz. However, as can be seen in Fig. 10g-j, the frequency slew rate limiter and the current slew rate limiter help to avoid a very fast transient from low network frequency conditions to normal network frequency conditions. However, there is still a very high power recovery period (although the system is in a safe condition). This was done intentionally to show that such a situation may happen and that some precautions must

Fig. 10. Network power-frequency support experimental results of Fig. 7.

be taken. This phenomenon can be avoided by increasing the time the slew rate limiter takes to ramp up the current reference.

The system was also tested for load-shedding. At 220.6s, the network frequency was dropped to 49.4 Hz, Fig. 11a. The frequency output of the slew rate limiter reached 49.52 Hz in about 1.5s. At this point the switches of the VSC were opened to stop the IM for this very low network frequency. Currents and powers (Fig. 11b) dropped to zero. The DC voltage (v_{dc}) is returned to its nominal value under no load conditions. By 243s the network frequency has returned to its nominal frequency, but the load remains disconnected. The restoration of the load must be made manually in this case as a safety

precaution; conditions for automatically restarting the load are beyond the scope of this paper.

E. Stability of the DC Voltage

The DC link dynamics are governed by the DC capacitance and by the nonlinear relationship between DC voltage, DC current and motor power demand. The small signal analysis governing the dynamics of the DC link reveals the existence of a negative impedance that could lead to instability of the AC drive [29]. If this is the case, the final torque command to the field oriented control can be further adjusted as recommended in [29] to achieved stabilization of the DC link.

Fig. 11. Load-Shedding experimental results of Fig. 7.

VI. WIDE PENETRATION OF SMART MOTOR DRIVE LOADS IN LARGE POWER SYSTEMS AND INTERACTION WITH TRADITIONAL GENERATOR FREQUENCY CONTROL

In EPNs most of the electricity is produced by large central generators, generally by synchronous generators driven by prime movers: usually turbines powered by steam, gas or water (hydro turbines). The turbine is equipped with a governor which in effect controls either its speed or output power according to its power–frequency characteristic [12]. For stable operation of the turbine, droop control is used for this purpose, as discussed in Section IV-A of this paper. The combination of many generation units helps to ensure that any power fluctuation produces small changes in the network frequency as shown in Fig. 3a.

Similarly, by combining the participation of many AC drives for network power-frequency support, a large amount of power reduction can be achieved if the network frequency were to drop as shown in Fig. 3b.

The interaction between the droop power-frequency characteristic of the synchronous generators and that of the load (AC drives) can be explained by analysing Fig. 12. In Fig. 12, if for some reason, the total load power were to increase from that required at point A to that required at point B, the network frequency would drop from f_{n0} to f_{n1} so as to cope with the new power demand. However, when the effect of the AC drives, equipped with a droop control, is considered, the resultant effect is slightly different. If the network frequency reduces, the power drawn by the AC drives reduces as well from that required at point C to that required at point D. This reduction in power allows the synchronous generators to accelerate and the system to achieve a different

Fig. 12. Equilibrium between the combined generators droop characteristic and the combined AC drive loads droop characteristic.

operating point (X) with a higher network frequency, f_{n2} , compared to that when no participation of the AC drives is considered (f_{n1}).

VII. CONCLUSIONS

Using AC drives as Smart-Loads is possible. Network power-frequency support is possible by fan loads powered by AC drives without overly disturbing the fan. When the electromechanical torque of the IM is controlled in open loop, the speed of the IM does not change quickly (but the electric power of the IM does). This is mainly due to cubic power-speed relationship and to the spare energy stored in the system inertia, which allows the fan load to reduce its speed slowly.

Such a disturbance would not have a huge impact on a fan used for heating, ventilation and air conditioning. However, such a reduction in power can help the recovery of the network under low frequency conditions or to avoid a worst case scenario. The functionality proposed in this paper is a relatively simple add-on that could be readily incorporated into standard commercial products. It is equally applicable to other machine types (e.g. PM, SR) and control methods (e.g. DTC, sensorless) since the frequency support algorithm only changes the reference torque command of the drive.

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IX. BIOGRAPHIES

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