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A Review of Source-Adaptive Variable Frequency Drive Starting Strategies: A PLC Based Approach for Mitigating Inrush Current in Weak-grid and Generator Fed Industrial System

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ABSTRACT: The squirrel-cage induction motor is a staple in industrial automation, but its use introduces electromechanical complexities during start-up. Thanks to Variable Frequency Drives (VFDs), the traditional starting torque-inrush dilemma has been largely averted with stiff, low-impedance grids, but the use of VFDs with isolated, high-impedance "weak grids", like dedicated backup generators, has created a new problem. This paper offers a review of the integration of VFDs with weak-grid sources. This review highlights the inefficiency of traditional passive mitigation approaches, such as generator over-sizing, Active Front End (AFE) converters and line reactors. This review recognizes the cost and efficiency drawbacks of such passive conventional mitigation strategies, and examines the transition towards active, software-based mitigation. In particular, it assesses the use of Programmable Logic Controllers (PLCs) for implementing dynamic, closed-loop adaptive acceleration schemes (such as parabolic S-Curves), as a highly viable, cost-effective approach to guarantee grid stability in Small and Medium Enterprises (SMEs)..

KEYWORDS: Variable Frequency Drive, Weak Grid, PLC, Adaptive Ramp Control, S-curve profile.

I. INTRODUCTION

The squirrel-cage induction motor is one of the most important parts of industrial automation, widely used for its ruggedness, reliability and low maintenance costs. While the design and operation of such machines is routine, it is a challenging and expensive process for system designers at start-up. At standstill (s=1), there is no back-electromotive force (back-EMF) and, as a result, the stator windings are effectively short-circuited, resulting in an massive current spike 500% to 700% of the rated full-load current of the motor [1]. The requirement to manage this huge peak current has grown rapidly, and is still driving innovation.

Specifically, the notion of starting torque-inrush management has advanced rapidly. As the needs of industry progressed, the design of the mitigation techniques evolved and transformed, and now they can be broadly grouped into two major categories based on technologies used as follows:

1. Electromechanical Methods: Conventional starting methods (e.g. Direct-On-Line (DOL) and Star-Delta starters). They are able to limit the initial voltage and current but they also reduce the starting torque to 33% and are not suited for high-inertia loads [2].
2. Power Electronic Technology: Contemporary methods based on Variable Frequency Drives (VFDs). Through the use of Pulse Width Modulation (PWM) to keep a constant Volts-per-Hertz (V/Hz) ratio, VFDs allow the motor to generate 100% of its starting torque while limiting inrush to 100% - 150% [3].

VFDs are ideal for current industrial applications as they provide the right balance between inrush and orque. Moreover, their ongoing advancement and adoption have transformed motor control techniques in heavy duty applications. While electromechanical approaches are easy to implement, they have been proven to be inadequate for the high starting torques in current applications. Alternatively, VFDs can help to smoothen transient mitigation. However, in relative simulations involving isolated, high-impedance networks (weak grids), it has been reported that conventional VFDs introduce novel, critical systemic instabilities by drawing instantaneous (non-mechanical and non-magnetic) active power from stand-alone back-up generators [4], [5]. The resulting power imbalance leads to excessive instantaneous spikes, sub-synchronous torsional interaction (SSTI) and systemic hunting [6], [8], [9].

This paper offers an in-depth review of the quickly emerging mitigation techniques for VFDs on weak grids. The dynamics between VFDs and high-impedance power sources have been identified, and the existing research on traditional hardware-based methods (e.g., generator oversizing, Active Front End (AFE) inverters, line reactors) have been reviewed and classified [10], [11], [13]. This paper goes beyond the traditional hardware-oriented reviews in assessing the transition to active, software-based mitigation. The benefits and drawbacks of incorporating Programmable Logic Controllers (PLCs) are weighed, and practical examples using adaptive acceleration control (e.g., S-Curve) are reviewed [18], [19], [22], [25]

The structure of the paper is as follows: Section 2 introduces the weak grid problem and theoretical causes of VFD instability. Section 3 reviews the current hardware-oriented approaches. Section 4 discusses and compares the move towards PLC integration and adaptive control. The concluding section presents the conclusion and suitability of software-defined mitigation for the industrial sector

II. THE WEAK GRID CHALLENGE AND VFD INSTABILITIES

Theoretical and practical performances of VFDs on "stiff" grids perfectly complement each other, but their integration into "weak" grids complicates matters. Weak grids, such as the isolated diesel generators commonly used by Small and Medium Enterprises (SMEs), have high source impedance (Zs) and low short-circuit capacity [4]. The coupling of VFDs to these generator-fed weak grids give rise to three stability problems.

1. Impedance and Voltage Sags: Ohm's Law states that voltage drop ($V_{drop} = IZ_s$) increases with current flow across a high-impedance source. Typical VFDs implement rigorous linear acceleration ramps, requiring continuous kilowatt demand in a straight line. This instantaneous and relentless kilowatt demand coupled with the effect of the rectification cycle draws the generator below its critical recovery threshold as seen in Fig 2, causing instantaneous voltage sag and engaging under-voltage relays [5][8].
2. The AVR Control Conflict: A VFD's interaction with a weak grid is first and foremost a competition between speeds. A VFD controls power in microseconds while the generator's Automatic Voltage Regulator (AVR) - which is based on spinning magnets - takes hundreds of milliseconds to react. The findings in [6] reveal that the interaction between high-power VFDs and turbine-generators frequently provokes Sub-Synchronous Torsional Interaction (SSTI), leading to negative electrical damping, dangerous system hunting and combined frequency and voltage instability.
3. Harmonic Heating: VFDs' non-linear rectifiers produce considerable Total Harmonic Distortion (THD). In weak grids, this non-linear load generates severe "flat-topping" of the generator's voltage, interfering with the AVR [8]. If unchecked, the ensuing third-harmonic circulating currents generate excessive heat, which is damaging the stator insulation [9]

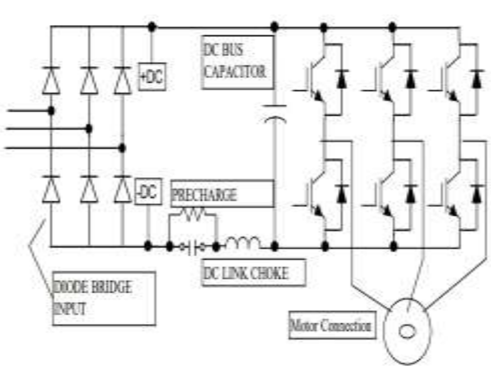

Figure 1. A VFD Circuit

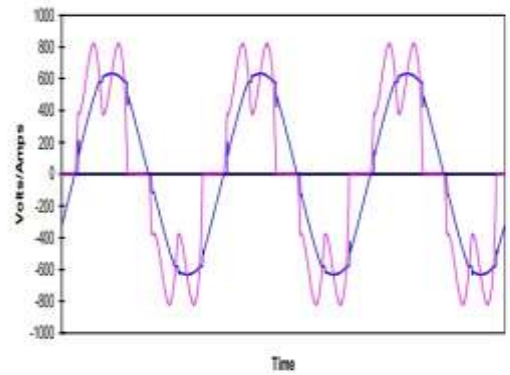

Figure 2. Graph showing voltage drop at peak

III. CRITICAL REVIEW OF HARDWARE CENTRIC MITIGATION TECHNIQUES

The conventional industrial solution to instability between VFD and generator has been ad hoc, involving large capital expenditure (CapEx) and brute force hardware over-engineering. An assessment of these approaches shows them to be costly:

A. Generator Oversizing

Generators have a much greater source impedance (subtransient reactance, in particular) than a utility grid. These harsh non-linear current pulses, when combined with this high impedance, result in significant voltage waveform distortion (voltage notching and harmonic distortion) in accordance with Ohm's Law ($V = IZ_s$).The brute-force industry standard solution to this problem (other than to install costly active harmonic filters) is to oversize the generator.

The most common industry standard practice is to buy generators that are 200% to 300% larger than the rated running kilowatt capacity required by the facility because the larger the generator, the smaller the generator's subtransient reactance, which makes for a "stiff" power source that can tolerate the non-linear pulses without significant voltage drops.[29]

Oversizing fixes the electrical issue, but introduces a mechanical problem. Diesel engines are heat designed to run at 70% to 100% of the rated load. At this low loading, the temperatures never reach a level to fully expand the piston rings. As a result, the rings don't seal well and unburned fuel and lubrication oil pass through to the exhaust manifold. This is a dark, oily "wet stack".[10]

B. Active Front End(AFE) Drives

Although 6-pulse Variable Frequency Drives (VFDs) are known for producing a substantial amount of low-frequency harmonic distortion in industrial power systems, Active Front End (AFE) drives offer a powerful alternative by replacing passive rectifiers with a controlled insulated-gate bipolar transistor (IGBT) bridge. Through fast Pulse Width Modulation (PWM) of the input current at high frequencies, AFE drives can offer almost unity power factor and less than 5% Total Harmonic Distortion (THD) in the input current.

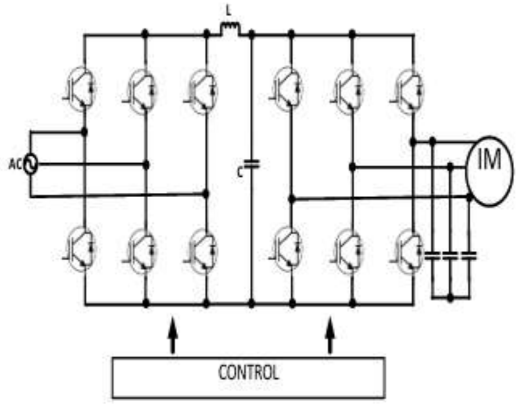

Figure 3. An AFE Drice Circuit

But this advanced harmonic reduction approach brings with it an important secondary issue surrounding protection. High-speed PWM switching (typically at 2-10 kHz) of the IGBTs creates severe Common-Mode Voltage (CMV) with a high rate of change of voltage ($\frac{dv}{dt}$). The high $\frac{dv}{dt}$ then couples with the line-to-ground distributed parasitic capacitance of motor cables and stator windings. According to the current through a capacitor ($I = C\frac{dv}{dt}$), this results in significant high-frequency leakage currents flowing through the system shielding and into the grounding grid [31]

As such, zero-sequence relays that are intended to react to actual ground faults by monitoring the vector sum of the three-phase currents often mistake high-frequency leakage that is normal to operation as a fault. This effect leads to nuisance tripping [30] which unintentionally shuts down essential industrial processes as well as compromises the control scheme. As a result, the plant engineers have to solve a high-frequency protection problem while addressing a low-frequency power quality issue.[13]

Also, the uptake of AFE solutions has been significantly limited by cost factors, especially for Small and Medium Enterprises (SMEs). The design of an AFE drive incorporates twice the number of semiconductors (from both IGBT bridges - input and output side), sophisticated digital signal processors for synchronized firing, and enormous line-side LCL (Inductor-Capacitor-Inductor) filters to smooth the switching ripple.[12] This hardware redundancy normally results in a capital cost for AFE drives two to three times that of conventional 6-pulse drives, making them prohibitive for standard SME applications.

C. Line Reactors

Line reactors are special inductors, placed in series with the VFD, to limit harmonic current flow. Although increased reactor impedance results in a smoother waveform, it inevitably results in a permanent (non-negotiable) voltage loss across the reactor [13]. With a 5% reactor at full load, 5% of the system voltage will be permanently dropped, inadvertently reducing the voltage available to the motor during peak demand times [14].

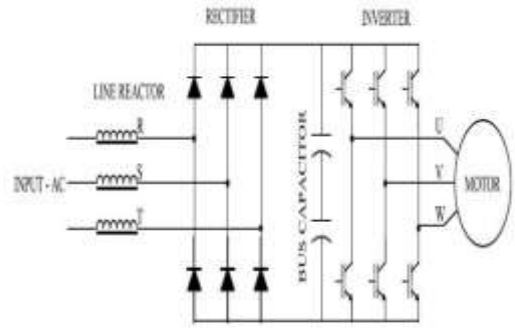

Figure 4. Line Reactor with VFD circuit

A variable frequency drive (VFD) using a conventional 6-pulse diode rectifier source pulses current from the AC mains in a non-linear fashion. To reduce the total harmonic distortion (THD), line reactors are connected in series with the VFD input. Electrically, a line reactor provides inductive ($X_L = 2\pi f l$) reactance. The basic inductance equation ($V = L\frac{di}{dt}$) indicates that the reactor resists sudden changes in current, which has the effect of broadening the current peaks and increasing the angle of conduction of the rectifier diodes[14]. Although higher inductance values of the reactor result in proportionally lower current THD, this comes at a high operational cost.

Based on their percentage impedance (%Z), Line reactors are classified into the Percentage Impedance (%Z) and Steady-State Voltage Drop-Line reactors. By design, a 5% line reactor is sized so that when the VFD draws its rated fundamental current, the voltage drop across the line reactor is 5% of the nominal system voltage.[34] Since this voltage drop ($V_{drop} = I \times X_l$) is dependent on the size of the load current, it is a dynamic penalty that is most severe when the load demand is highest.[32]

The key problem with the AC voltage drop is its effect on the DC bus of the VFD. The DC bus voltage is directly proportional to the peak of the input AC line voltage (ideally $V_{dc} = 1.35\ V_{ll}$ for a three phase supply). A persistent 5% AC voltage drop across the reactor will require a commensurate suppression of the DC bus voltage.

The VFD inverter stage depends on the DC bus to produce the AC voltage output to the motor with Pulse Width Modulation (PWM). If the DC bus is "clipped" by the line reactor, the VFD's ability to supply a full-rated AC voltage is "clipped". If the motor is operating at its base speed (100% of design speed) and is heavily loaded (peak torque) by the mechanical load, the motor will require the full 100% of its rated terminal voltage to maintain its optimal Volts-per-Hertz (V/Hz) ratio and nominal stator flux.

The inability to supply the rated voltage due to the DC bus suppression caused by the reactor causes the motor to prematurely "weaken its field." In order to provide the required mechanical torque at a reduced voltage, the induction motor draws more current, which leads to increased slip, excessive overheating (I^2R losses) and the risk of motor stall during peak demand periods [33].

IV. THE TRANSITION TO PROGRAMMABLE LOGIC AND ADAPTIVE RAMP CONTROL

Traditionally, voltage instability and harmonic distortion issues have been tackled through the static over-design of hardware components, such as using enormously sized generators or line reactors. But with the cost-effectiveness and space constraints of static power hardware, recent literature proposes a shift: from static hardware to smart logic controllers. Today's Programmable Logic Controllers (PLCs) offer the dynamic feedback control needed to intelligently coordinate the load with the source**.**

A. Source Adaptive Logic

Conventional Variable Frequency Drives (VFDs) are "open-loop" loads as seen by their power source; they blindly follow their pre-programmed linear acceleration ramps, regardless of the grid to which they are connected - a strong utility grid, or an extremely weak isolated diesel generator. This lack of "awareness" is a key driver of voltage transients in weak grids. Through the addition of a PLC that incorporates industrial fieldbus networks (PROFINET, Modbus TCP) and SCADA features, the electromechanical system is given a "mind's eye" [37]**.** Using digital handshakes, the PLC is programmed to dynamically monitor grid variables specifically terminal voltage and source impedance profiles and use ladder logic programs to tell the VFD its best, dynamically computed acceleration profile**.**

B. S-curve motion and Freeze profile

The supervisory PLC is programmed to dynamically re-map the VFD default linear ramp to a parabolic acceleration profile (commonly referred to in control theory as an S-Curve) when operating on a weak, high-impedance source. The need for the S-Curve is evident from the electromechanical derivatives of motion. For a linear ramp in velocity, the acceleration must undergo an instantaneous step-change. Mechanical torque is proportional to angular acceleration ($T = J \times \alpha$), so an instantaneous change in acceleration requires an instantaneous step-change in active electrical current (I_q) of the generator. This step-change ($\frac{di}{dt}$) also interacts with the generator's subtransient reactance and leads to significant instantaneous voltage drops.

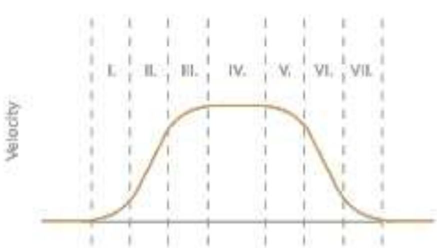

Figure 5. S-Curve Profile

As has been shown extensively in modern motion control literature, an S-Curve overcomes this problem by imposing a finite limit on the "jerk" (the first derivative of acceleration with respect to time $j = \frac{da}{dt}$)[35]. By using a polynomial or parabolic curve, acceleration is applied gradually. As a result, the slope of the current drawn from the generator ($\frac{di}{dt}$) is constrained to a mathematical value that matches the time constant of the diesel engine governor and the time constant of the Automatic Voltage Regulator (AVR). This algorithmic constraint completely eliminates the initial starting paradox and completely avoids the initial low voltage crash.

C. Algorithmic Undervoltage Ride-Through and Freeze Logic

Moreover, the use of a PLC enables active and closed-loop feedback-based algorithms that mimic sophisticated undervoltage ride-through functions. A very effective algorithmic approach is to issue a "Voltage Freeze" command [36] . If during the acceleration phase of the motor the PLC senses that the bus voltage has fallen below a threshold (e.g., 90% of nominal V_{ll}), the logic controller immediately pauses the VFD ramp.

This pause freezes the acceleration in its current position, so that the motor no longer requires an extra increment of active power, thus preventing an increase in electrical demand. This short freeze allows the generator's turbocharger time (typically a few microseconds) to accelerate, and the AVR to increase the field current to restore the grid voltage. After the PLC reports the terminal's voltage has risen to a safe level (e.g., 95%), the freeze command is lifted and the motor's S-curve acceleration continues. This feedback dance ensures the load does not exceed the power source's ability to recover

CONCLUSION

Existing literature shows that conventional, hardware-based mitigation methods are economically and technically unviable for managing the complex electromechanical interactions between VFDs and high-impedance generator systems. Generator upsizing and passive filtering do not solve the active power step-load problem. In contrast, a software-based, PLC-implemented adaptive strategy provides effective and permanent mitigation. The use of low-cost micro-PLCs to perform closed-loop trajectory control (e.g. dynamic S-Curve profiling) offers a new way to permanently stabilise isolated power grids. This allows for safe motor starts, increases equipment lifetimes and closes the current gap between hard power electronics and dynamic power grid constraints without unrealistic capital costs.

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