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Application of SRF-PI Current Control in the Design of a Single-Phase Asymmetrical Inverter for Use in Weak Grid Environments

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Abstract: The power stage circuit and control system of the ACHMI uses a dual-loop current control mechanism in the hybrid reference frame (HRF), a synchronous reference frame phase-locked loop (PLL), and a hybrid modulation technique to generate a multilevel output voltage. The complete ACHMI system's small-signal model is derived using a simple, step-by-step derivation approach. Small-signal analysis is used to linearize the ACHMI system, which yields a model of its impedance. In addition, a refined impedance stability criterion is developed and used to analyse the robustness of the system under investigation. By adjusting the PLL bandwidth, output power factor angle, and grid current reference signal amplitude in the presence of poor grid conditions, the ACHMI's stability can be evaluated. This research suggests a methodical design procedure for choosing the PLL proportional-integral (PI) controller to guarantee steady-state performance and dynamic response in an ACHMI system. Finally, the theoretical theory is verified by modelling and real findings from a scaled-down grid-connected ACHMI prototype system.

Keywords: Single-Phase, Weak Grid Condition, Synchronous Reference Frame, Asymmetrical Inverter, PLL bandwidth

Introduction

CHMI convert DC power from distributed power generating systems (DPGS) into dependable grid-injected AC power [6-12]. CHMIs are more popular than single-phase H-bridge, diode-clamped, and capacitor-clamped inverters due to their modular architecture and scalability to higher input voltages. The asymmetrical architecture is more appealing than the symmetrical one since it can provide more output voltages [13]. The literature (ACHMI) is mostly focused on asymmetrical cascaded H-bridge multilevel inverter modulation and control [14]. The stability research of the single-phase grid-connected ACHMI system is incomplete. A grid-connected inverter's stability depends on current management and phase-locked loop (PLL) performance [15-21]. Two standard PI controllers with identical parameters form the SRF-PI control scheme, initially devised for three-phase PWM converters but now applicable to single-phase systems [22]. Using a proportional controller in the stationary frame to operate the inner current loop is the easiest way to manage current and increase dynamic performance [23-25]. This study examines how PLL, reference current amplitude, and power factor angle affect LCL-type single-phase grid-connected ACHMI systems and recommends PLL parameter design. We investigate the hybrid modulation technique and the hybrid reference frame double-loop current control approach to ensure stability analysis robustness [26-33]. Dispersed high-power distributed power production devices make a power distribution grid vulnerable [34-39]. Grid resistance causes harmonic resonance and instability in grid-connected inverters [40]. Thus, grid-connected inverters' reliability at high grid impedance should be investigated (fig.1).

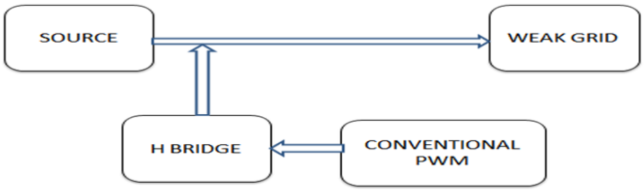

Fig. 1: Existing Block Diagram

Literature Survey

Renewable energy sources like wind, solar, and hydro, as stated by Blaabjerg et al. [1], are a dependable substitute for conventional energy sources like oil, natural gas, or coal. Germany, Denmark, Japan, and the United States are at the forefront of the worldwide expansion of distributed power generation systems (DPGSs) that rely on renewable energy sources. New and stronger criteria for power quality, safe running, and islanding protection are released as the number of DPGSs linked to the utility network rises. As a result, there is a need to better regulate DGSs so that they can be connected to the grid. This document provides a summary of the designs for DPGS using fuel cells, PV, and wind power. Low-order harmonic compensation is also covered, along with the control mechanisms of the grid-side converter. In addition, solutions for controlling operations in the presence of grid failures are discussed. This study concludes with a discussion of the significance of synchronisation techniques from a control standpoint.

According to Harnefors et al. [2], a grid-connected voltage-source converter's interconnection stability can be evaluated using the passivity qualities of the VSC's input admittance (VSC). In general, instability of the grid is avoided if critical resonances occur in places where the input admittance acts passively, i.e. has a nonnegative real portion. Expressions for the input admittance are produced by space-vector modelling of VSCs, which is covered in this study as part of an overview of passivity-based stability assessment. We also provide design suggestions for reducing the size of the negative real-part region.

Cascaded multilevel inverters, as stated by Malinowski et al. [3], provide a medium-voltage output by connecting power cells with conventional low-voltage component topologies in series. Because of the built-in redundancy of the individual components, superior output voltages, input currents, and reliability can be attained. Because of these benefits, the cascaded multilevel inverter is now considered a viable option for medium-voltage applications. In this study, we take a look at the various control methods and modulation techniques that are employed by these inverters. Both advanced and regenerative topologies are covered. We demonstrate some real-world uses for these characteristics. The discussion concludes with a look towards the future.

Recent applications of multilevel converters have been highlighted, as examined by Ajami et al. [4], due to benefits such as a higher quality output waveform, less harmonic distortion, and less electromagnetic interference. There are, however, downsides to using such converters, such as the need for more parts (such as switches and DC power sources) and more complicated control methods (such as pulse width modulation). In this research, a novel multilevel converter known as a "cascade-multi-cell" converter is presented. To begin, the fundamental components of the suggested multilevel converter have been described. After that, both symmetric and asymmetric arrangements are shown. In comparison to a standard cascade converter, the proposed architecture requires fewer switches and gate driver circuits. This means the voltage it produces will be raised. In addition, the suggested topology reduces the conductive losses by reducing the number of on-state switches. The suggested converter achieves the same peak inverse voltage as the conventional cascade converter. At last, the outcomes of both the simulation and the experiment are shown. Validity and efficiency of the proposed multilevel structure are demonstrated by the findings presented.

According to Townsend et al. [5], the switching states in a multilevel H-bridge StatCom are redundant. The H-bridge capacitor voltages are equalised, current reference tracking is great, and switching losses in the converter are reduced thanks to a novel take on the standard model predictive control approach developed in this study. Heuristic models of voltage balancing and switching loss characteristics are incorporated into a dead-beat current controller to form the scheme. Pulse width modulation's incorporation is also detailed. The correct control and modulation procedures have been demonstrated to work in simulations and experiments. We compare the key performance indicators of multilevel H-bridge StatComs to those of conventional control and modulation methods.

Proposed System

In this study, we take into account the robustness of the stability analysis by considering both the hybrid modulation strategy and the double-loop current control approach that is constructed in the hybrid reference frame [41=43]. It is common knowledge that one-phase systems can be modelled with the help of Linear Periodic (LTP) theory. Harmonic linearization applied to an average model of the investigated single-phase system yields the LTP model. In order to use LTP, a full-order differential equation model of the system must be linearized. In contrast to the standard H-bridge inverter, the single-phase asymmetric cascaded H-bridge inverter contains more moving parts [44-49]. In addition, the system under study features a dual-loop current control method that incorporates both an inner current loop that feeds back the current through the LCL-filter capacitor and an exterior grid current loop [50-54]. For accurate current regulation of the grid-connected inverter, the controller for the grid current must be carefully chosen [55].

This work employs a hybrid reference frame to implement a dual-loop current control method [56-61]. Different from the dq frame's modelling approach, the system model is then constructed in the hybrid reference frame. A standard SRF-PLL is used for grid synchronisation to keep the stability analysis as generic as possible. The theoretical study, simulation, and experimental results all corroborate the reliability of the modelling approach. This paper's primary contributions are summed up as follows. In this study, we propose a hybrid frame double-loop current control approach for controlling LCL-type grid-connected single-phase ACHMI, where the outer current loop is controlled in the dq frame and the inner control loop is implemented in the stationary reference frameb[62-71]. Using a straightforward iterative computation procedure, a small-signal model of the single-phase ACHMI with this control technique is created. 2) The single-phase ACHMI system is modulated by the hybrid modulation technique. The effects of a little disruption on hybrid modulation are analysed in depth [72-80].

By synthesising an output voltage that has lower harmonic content, the multilayer inverter is an effective option for medium and high power systems [81-85]. The term "multilevel" describes a system in which numerous "stages" of inverters are connected in series to provide the desired "levels" of output voltage. Harmonic distortion can be reduced by increasing the number of levels. Based on their unique architectures and modulation methods, the three topologies—flying capacitor (FC), neutral point clamped (NPC), and cascaded multilevel inverters (CMLIs)—are each best suited to specific uses. Among the three topologies, CMLI is the most preferred for the interconnection of renewable energy systems due to its many benefits, including its elimination of the voltage unbalance problem, its ability to adapt to low switching frequencies, and the fact that it does not require clamping capacitors or

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diodes. Multilevel inverters can be found in a number of different topologies. The input voltage source and switching mechanism are what set multilayer inverters apart [86-91].

Cascaded H-Bridge Multilevel Inverters

The sinusoidal output voltage is generated by a succession of H-bridge inverters in this inverter. In an H-bridge multilevel inverter, the number of output voltage levels is 2k+1, where k is the number of cells in the inverter. Each cell in the inverter contains one H-bridge, and the output voltage is the sum of the voltages created by each cell. This sort of inverter has an edge over the other two since it requires less components, resulting in a lighter and cheaper unit [92-96]. A single-phase inverter has only one DC source for each phase. There are positive, negative, and zero voltages produced by each tier. The DC output in conjunction with the AC input and the four switches in various configurations. Keeping two switches in opposite places on keeps the inverter on. When all the inverters are turned on or off, it will shut off. Total harmonic distortion can be reduced by defining and using appropriate switching angles [97-101].

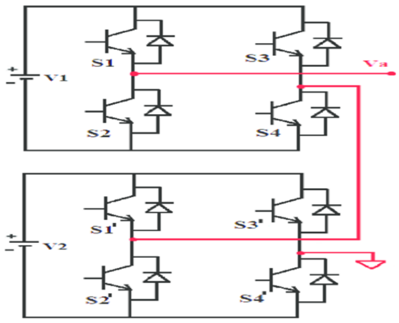

Fig. 2: H-Bridge inverter

The sinusoidal output voltage is generated by a succession of H-bridge inverters in this inverter. In an H-bridge multilevel inverter, the number of output voltage levels is 2k+1, where k is the number of cells in the inverter. Each cell in the inverter contains one H-bridge, and the output voltage is the sum of the voltages created by each cell. This sort of inverter has an edge over the other two since it requires less components, resulting in a lighter and cheaper unit [102-109]. A single-phase inverter has only one DC source for each phase. There are positive, negative, and zero voltages produced by each tier. You can achieve this by using the DC output in conjunction with the AC input and the four switches in various configurations. Keeping two switches in opposite places on keeps the inverter on. When all the inverters are turned on or off, it will shut off [110-115]. Total harmonic distortion can be reduced by defining and using appropriate switching angles.

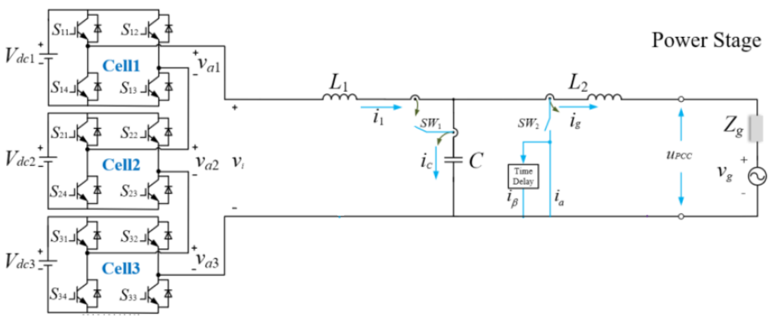

Fig. 3: Single-phase LCL interfaced grid-connected ACHMI system

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Operation of the proposed design

The output of the PI controllers is then converted back to the reference frame using the inverse Park's transformation, with the axis-referenced output current iC,* serving as the transformation's basis [116-121]. Active damping is the primary function of the proportional controller K in the inner current ic loop, which also enhances the dynamic performance of the system. After that, the signal Um at the end of the inner current loop is modulated using the modulation signal acquired from the outer current loop. The hybrid modulation approach is used because of the significant differences between the examined inverter topology and the standard single-phase two-level grid-connected inverter design (fig.3). This paper analyses the hybrid modulation technique in order to systematically evaluate the stability of the LCL-type single-phase grid-connected asymmetric cascaded H-bridge multilevel inverter [122-124].

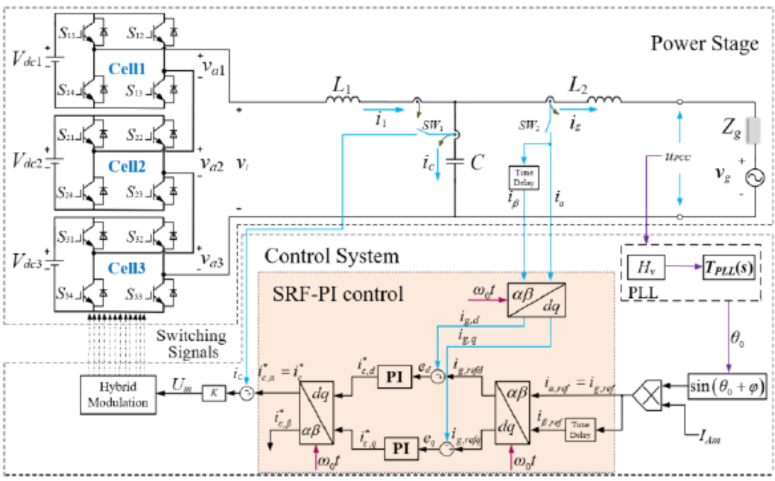

Fig. 4: Proposed controlled design

Technical Description

Over-modulation can be prevented by having Cell1 produce the unmodulated component at the desired comparative level (h3, h2) [125-131]. Using SimPower Systems, we construct a model of a system in the same way that we would a physical one. Ideal conduction paths are represented by the physical connections between the model's components. With this method, rather than deriving and executing the equations for the system, the physical structure of the system is described. The model, which is similar to a schematic, is used by SimPowerSystems to automatically generate the differential-algebraic equations (DAEs) that characterise the behaviour of the system. The Simulink model incorporates these equations seamlessly. With Sim Power Systems' sensor blocks, we can take readings of your power network's voltage and current and send them on to regular Simulink blocks. By utilising source blocks, electrical signals in Simulink can be assigned values for current and voltage [132-137]. A Simulink-created control algorithm can be integrated into a SimPower Systems system through the use of source and sensor blocks.

Modelling Custom Components

The basic elements in SimPowerSystems' libraries, when combined with Simulink blocks, allow for the modelling of bespoke components.

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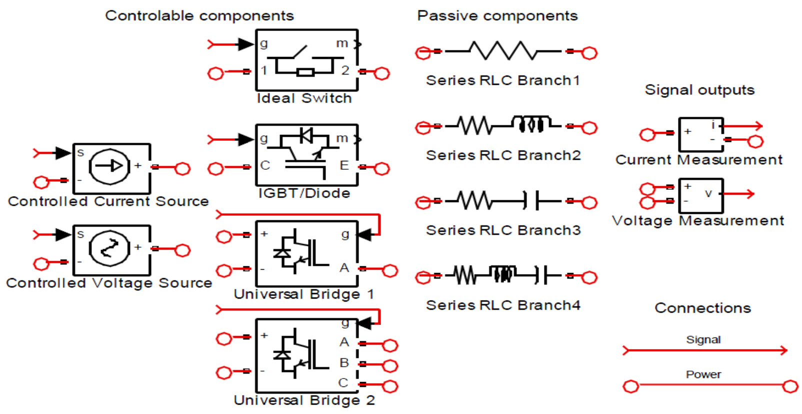

Fig. 5: Simpower System Libraries

Simulink is compatible with a wide range of hardware and software from MathWorks and beyond. For instance, Stateflow adds a flowchart and state machine design environment to Simulink. When used in tandem with MathWorks' Simulink Coder, Simulink may automatically create C source code for use in implementing real-time systems. Because of its adaptability and potential for rapid iteration, this is becoming increasingly popular as a tool for embedded system design work, and it is also seeing increasing application in production systems [138-141]. The code generated by Embedded Coder is suitable for usage in real-time devices. Models can be verified and validated systematically with the help of Simulink Verification and Validation by means of evaluating the modelling style, tracing the requirements, and analysing the model's coverage [142-149]. The Simulink Design Verifier provides test case scenarios for model verification in the Simulink environment and employs formal approaches to detect design problems including integer overrun, division by zero, and dead logic. In order to undertake a formal verification and validation procedure on Simulink models, the developer can produce inputs using the systematic testing tool TPT. By switching out the Constant and Signal generator blocks in Simulink, the stimulation may be replicated. The suggested converter's hardware is built on a PIC microcontroller. The PIC controller's pulses are programmed using software packages like Proteus, Mplab, and Micropro. The pulses to the MOSFET are driven by a PIC and driver circuit, both of which are controlled by the power supply circuit (fig.6).

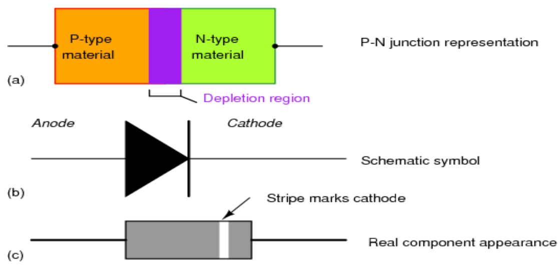

Fig. 6: Diode

The nonlinear resistance and conductance of a diode set it apart from other two-terminal electrical components, such as the two-terminal linear resistors that follow Ohm's law. These days, the vast majority of diodes are semiconductor diodes, which consist of a crystalline semiconductor material coupled to two electrical terminals. Diodes are vacuum tubes having two electrodes, a plate and a cathode, and they are almost extinct outside of high-power technology. The forward direction of an electric current is called the "ahead" direction of a diode because it allows current to flow in that direction while blocking current in the "reverse" direction (the reverse direction). Therefore, the diode can be compared to a check valve in a mechanical system. Rectification refers to the process of changing AC current into DC current and is used in radio receivers to remove modulation from incoming signals. Diodes function as rectifiers. Diodes, however, are capable of more complex behaviour than just turning on and off. The threshold voltage must be reached in the forward direction for a semiconductor diode to begin conducting electricity (a state in which the diode is said to be forward-biased). Because the voltage drop across a forward-biased diode is rather constant regardless of current, this effect can serve as a voltage reference or temperature sensor. The nonlinear current-voltage properties of semiconductor diodes can be adjusted by changing the semiconductor materials and doping the materials with impurities. Diodes designed for certain purposes take use of this. Diodes have many applications, including voltage regulation (Zener diodes), surge protection (avalanche diodes), electronic tuning of radio and television receivers (varactor diodes), generation of radio frequency oscillations (tunnel diodes, Gunn diodes, IMPATT diodes), and light generation (diodes) (light emitting diodes). Because of their negative resistance, tunnel diodes can be advantageous in some circuits (fig.7).

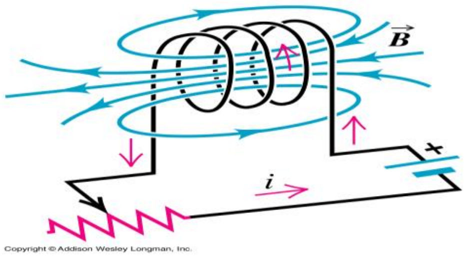

Fig. 7: Inductor

The magnetic field created by an inductor (also known as a reactor or coil) stores electrical energy. Inductance can be created by any conductor, though most inductors are made by winding the conductor into loops to strengthen the magnetic field. Faraday's law of electromagnetic induction states that a voltage is induced within the coil as a result of the time-varying magnetic field; this voltage is in opposition to the change in current that caused it, as stated by Lenz's law. Due to its capacity to delay and bend alternating currents, inductors are one of the fundamental components used in electronics where current and voltage vary over time. Choke inductors are commonly used in power supply filters and circuits where AC signals must be suppressed. Some switched-mode power supply employ an inductor as the energy storage mechanism. The inductor is active for a discrete subset of the switching frequency of the regulator and is disabled during the remaining time. The input-to-output voltage ratio is established by the energy transfer ratio. In conjunction with an active semiconductor device, this XL allows for extremely precise voltage regulation (fig.8).

Fig. 8: Capacitor

An electrical component with two terminals that retains energy in an electric field is called a capacitor (or condenser in older literature). Even though capacitors come in a broad variety of shapes and sizes, they all have two electrical conductors separated by an insulator (dielectric), with metal foils being a popular structure. Many typical electrical gadgets include capacitors as essential

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components of their electrical circuits. A static electric field forms across the dielectric when there is a potential difference (voltage) across the conductors, resulting in a positive charge collecting on one plate and a negative charge collecting on the other. The electrostatic field is a reservoir for energy. Capacitance, expressed in farads, is the solitary unchanging property of an ideal capacitor. This relates the amount of charge on each conductor to the difference in potential.

Capacitor conductors are commonly referred to as "plates," a reference to an early method of construction, because the capacitance is highest when there is a narrow spacing between large sections of the conductor. The breakdown voltage occurs because the dielectric between the plates leaks a small amount of current and has a maximum allowable electric field strength. Also, the conductors and leads add some extra resistance and inductance that isn't wanted. Electronic circuits rely heavily on capacitors for many different reasons, including filter networks, smoothing the output of power sources, resonant circuits used to tune radios to specific frequencies, and many more. A linear regulator is a voltage stabilisation component used in electronics. The regulator's output voltage remains stable because its resistance fluctuates in response to the load. The switching regulator, on the other hand, is literally just a switch. The circuit controls the on/off frequency of this switch, which is typically between 50 kHz and 100 kHz. A voltage divider network is constantly adjusted by the regulator, making it behave like a variable resistor and ensuring a stable output voltage. High efficiency, much less heat, and smaller size are the key benefits of a switching regulator versus a linear regulator.

A potential divider is employed with the transistor (or equivalent device) as one half to determine the regulated output voltage. To control the transistor, a signal is generated by comparing the output voltage to a reference value and sending that signal to the transistor's gate or base. Negative feedback and an appropriate compensation method maintain a steady voltage at the output. Since the transistor behaves like a resistor, the linear regulator will waste electrical energy by turning it to heat, making the regulator inefficient. Multiplying the current by the voltage drop across the transistor gives the amount of power lost due to heating. In many cases, a switched-mode power supply may do the same job more efficiently. For low loads or when the target voltage is close to the input voltage, a linear regulator may be the better choice. In such circumstances, the linear regulator could waste less energy than a switcher. The linear regulator doesn't need any noisy, complicated, or expensive magnetic devices (inductors or transformers) to function. There are two primary types of linear regulators, known as series regulators and shunt regulators.

The more typical type of regulator is a series regulator. Using a variable resistance (the main transistor is located in the "upper half" of the voltage divider), the series regulator connects the supply voltage to the load. The power consumed by the regulator is proportional to the product of the power supply's output current and the regulator's voltage drop. The shunt regulator is a voltage divider in which the primary transistor is located in the "bottom half," providing a conduit from the supply voltage to ground through a changeable resistance. Shunt regulators are even less efficient than series regulators since the current flows to ground instead of the load. However, it is utilised in very low-powered circuits where the wasted current is negligible, and it is often simpler, consisting of nothing more than a voltage-reference diode. Voltage reference circuits typically take this shape. A linear regulator requires an input voltage that is at least as high as the desired output value. The dropout voltage quantifies the absolute minimum that can be achieved. In order to maintain their 5V output, standard regulators like the 7805 require an input voltage of at least 7V. As a result, the voltage at which it drops out is 2V (7V -5V). When the supply voltage is less than 2V above the desired output voltage, as is the case in low-voltage microprocessor power supplies, a low dropout regulator (LDO) is used. Having an output voltage higher than the input voltage is fatal to a linear regulator (not even an LDO). In this case, a switching regulator would be ideal.

Conclusion

The load is the circuit linked to the output terminal (or the input impedance) of an electric circuit with a clearly defined output terminal. (The term 'load' may also refer to the power consumed by a circuit; that topic is not explored here). Sensors, voltage sources, and amplifiers are all examples of circuits whose performance degrades under load. One simple example is the power supplied by a standard wall outlet, which maintains a steady voltage and whose load consists of all the appliances plugged into it. When a high-powered appliance is turned on, the load impedance drops significantly. If the load impedance is not significantly

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greater than the power supply impedance, the voltage will drop. In a home, turning on a heater or fireplace could cause the incandescent lights to dim substantially.

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