

Simulink-Based SVPWM Current Control Technique for Multilevel Diode NPC Inverter Topologies

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Abstract

The constant concern about environmentally friendly solutions in the modern world has encouraged most companies to rethink their strategies and to design new, or improved, methods and products. This is not different regarding electrical energy generation, in which solar and wind energy have been leading as green methods. Based on the fact that these resources are transients, one of the fundamentals that is constantly being improved on with these methods is the efficiency of the energy conversion between direct current (dc) to alternating current (ac) in order to reduce energy generation losses. Therefore, improved inverter methods have been designed and implemented on both solar and wind power plants, especially the neutral-point clamped (NPC) inverter. The NPC is applied to photovoltaic (PV) panels and has several advantages over other methods, but it can be improved in several ways. Improving its number of levels, implementing more complex control methods, and employing faster power control loops are proving essential in its implementation.

Introduction

Electricity conversion is a continuous need of the modern world. Alternating current sources are constantly being rectified to power electronic devices and batteries, while direct current sources, such as a battery in an electrical grid fault, must be immediately converted to ac in order to supply the devices connected to them.

Moreover, with the constant concern about environmental solutions regarding clean electrical energy generation, the lack—or intermittence—of resources to generate it, and geographic constraints in order to supply the exponentially increasing population needs, alternative means of electricity generation have been exploited. These are mainly solar and wind energy, which essentially do not exhaust any resources and can be employed almost everywhere.

However, environmentally friendly methods to generate energy rely on transient resources such as the sun and the wind—hence one important way to improve these methods is to increase their efficiency. Besides, variations in the loads using this electricity and the effect of the reactive power in the system, which introduces harmonics, deteriorates the quality and reliability of the electric distribution network. Consequently, most companies had to rethink their products, policies, and plans so they could meet the modern world's expectations and standards.

In fact, as the resources needed for green energy generation are nature related and cannot be controlled, as well as the grid electricity utilization by the population, companies have been constantly focusing on improving their technology, especially to increase the efficiency of electricity generation and utilization.

Based on this, new and improved methods that have been applied on photovoltaic panels and wind turbines are being constantly shaped. The cornerstone of this process is to convert the dc generated to ac so it can fully perform as an energy source. In fact, this process is performed by the inverter, which is mainly responsible for grid synchronization and energy conversion. Thus, improving this system allows it to have an increase in efficiency and to be more affordable for their customers.

There are several inverter topologies that vary from off-grid and grid connected inverters, which can also be transformer-based or transformerless inverters, and that are operated in an open-loop or closed-loop manner. These topologies can also have different levels that influence the resolution and switching pattern of the inverter. Furthermore, these settings determine the size, weight, price, complexity, operation, harmonic generation, utilization, efficiency, and so on, that directly affect the final product.

Among the transformerless photovoltaic inverters, there are two main families of converters, these being the H-bridge (or full-bridge) and neutral-point clamped (NPC). Apart from the classical implementations, in each of these families there are several variations with different specifications and characteristics, which make them more suitable for specific applications.

Besides the inverter, a modulation technique must be implemented in order to modulate the inverter's conversion. There are several types of pulse-width modulation (PWM) techniques that can be applied to inverters

and motor drivers, which include sinusoidal pulse-width modulation (SPWM), space vector pulse-width modulation (SVPWM), shift-phase PWM, and selected harmonics elimination PWM. While there are several modulation techniques, with each of them being more suitable for specific applications, the more versatile modulation strategies to employ with PV inverters are SPWM and SVPWM, due to the wide range of switching frequencies, and to ease the implementation in multilevel inverters. However, as the SVPWM operates as a combined effect of all the three phases of the inverter's output instead of single phases, it has become the more popular and well-established technique to be employed in 3-phase inverters and multilevel inverters.

Furthermore, one of the fundamental requirements for a grid-connected converter is grid synchronization. This requirement is directly correlated to the converter's efficiency and there are different ways of implementing it. A phase-locked loop (PLL) connected to the grid, for instance, is often used to fulfill this requisite.

This article mainly describes an SVPWM current control technique for multilevel, 3-phase NPC inverter topologies, focusing on three- and five-level topologies implemented with a closed-loop vector control and positive-sequence voltage detector to stabilize any grid fault. This article focuses on PV applications and all the results presented in it were acquired by simulating the system in the MathWorks® software, Simulink®.

Diode Neutral-Point Clamped Topologies

A diode NPC topology is formed by a combination of insulated-gate bipolar transistors (IGBT) and diodes. Structurally, the NPC is designed such that by clamping the PV panels to the grounded middle point of the dc bus using diodes, the zero voltage can be achieved.

This inverter has several advantages over the H-bridge topology, which makes it more suitable for implementation as an inverter for high efficiency PV panels. For instance, while it was implemented later than the H-bridge, it achieved improvements in comparison to the classical full-bridge implementation, such as lower dv/dt and switch stress. Moreover, its versatility allows it to be used as a single-phase and 3-phase inverter, since it can be implemented as a 3-phase, 4-wire converter.

This topology has several other advantages over other topologies, such as the unipolar voltage across the filter, which lowers core losses. It exhibits high efficiency (up to 98%) since there is no reactive power exchange between the inductance in its output and the capacitance in its filter during the zero voltage, and it also yields very low leakage current and produces low electromagnetic interference.

However, this topology is mainly used in 3-phase PV inverters with mini-central, since it is more complex to implement than H-bridge topologies. It is also more suitable for high power applications, such as central inverters.

Furthermore, with the increase in electricity demand, the inverters have been improved to generate more voltage levels. The more voltage levels an inverter has, the better the quality of its ac output, due to the lower distortion that higher levels cause in the output voltage than lower levels, increasing overall system efficiency. Besides, the number of levels brings a trade-off between the switching losses and the conducting losses, where the latter increases according to the increase of levels while the switching losses reduce. Thus, multilevel inverters reduce stress for the semiconductor components, lowering failures and extending the life of the inverter's components. As a matter of fact, the multilevel NPC inverter

experiences a reduction of total harmonic distortion (THD), undergoes a reduction of switching frequency of each device—reducing the total power loss, does not require step-up or step-down transformers, requires smaller ac filters, and reduces electromagnetic-compatibility issues.

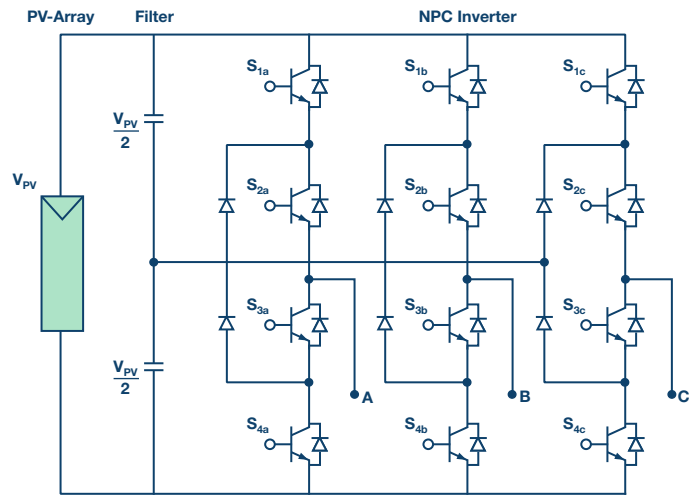


Figure 1. Three-level diode NPC topology.

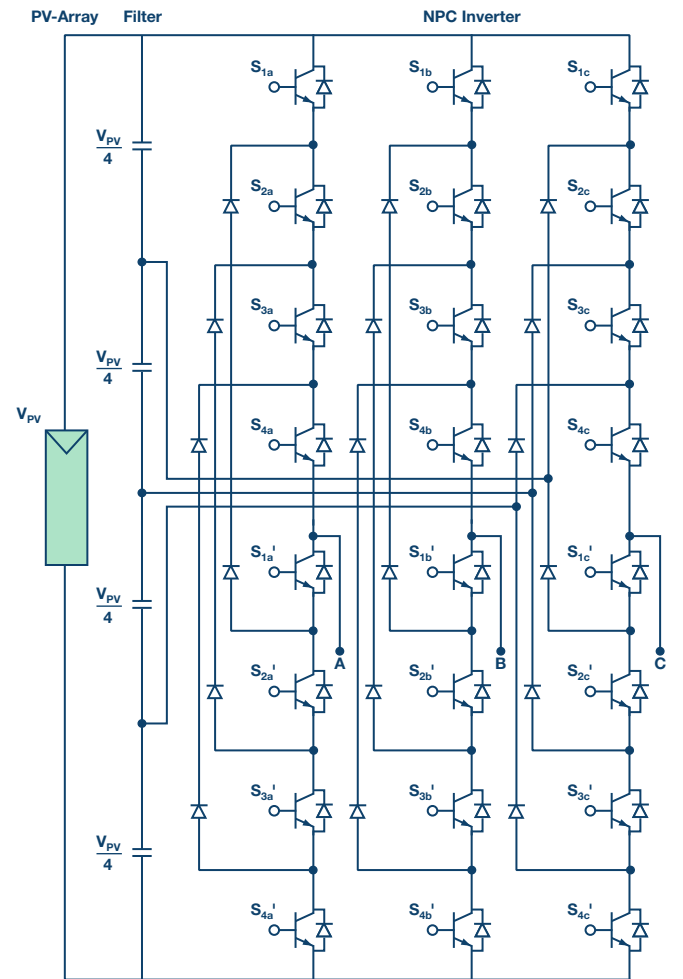


Figure 2. Five-level diode NPC topology.

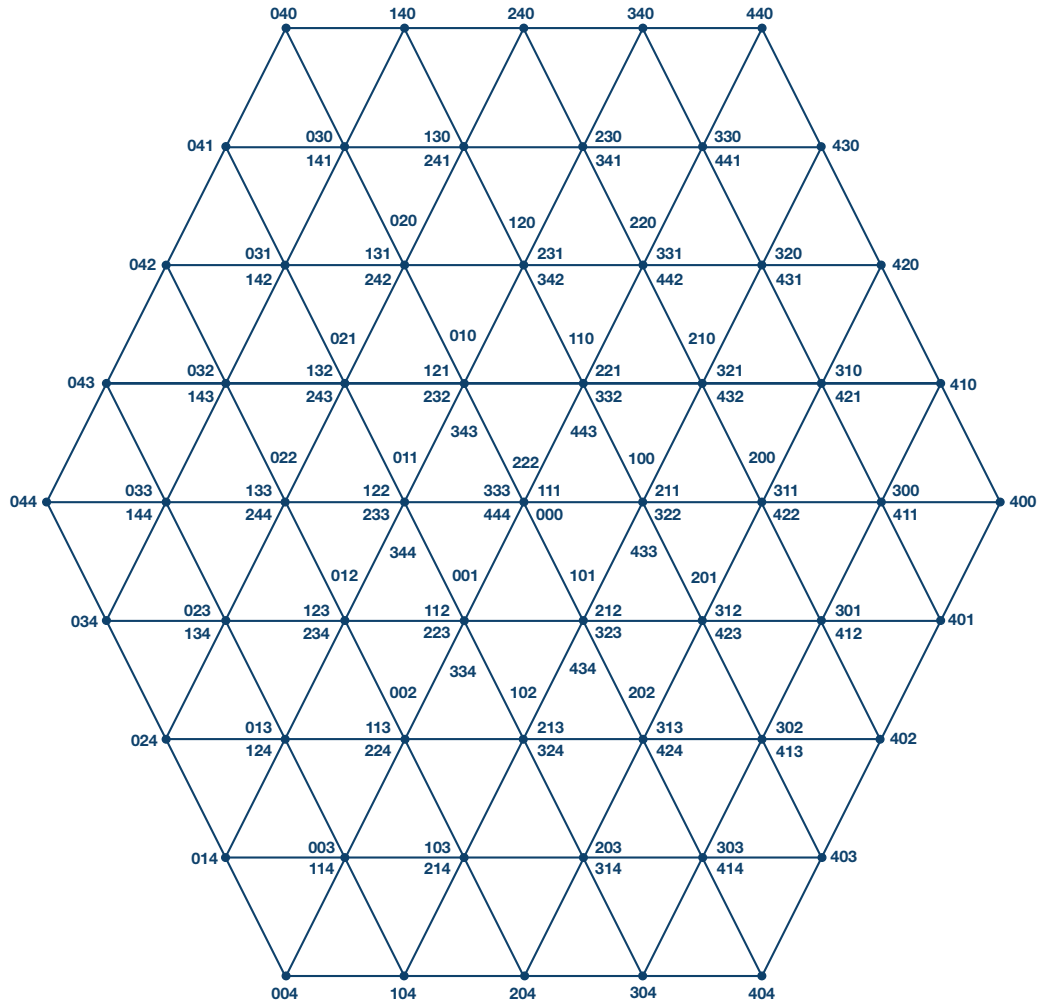


Figure 4. Five-level space vector diagram.

SVPWM Generalized Closed-Loop Vector Control and Reactive Power Control Method

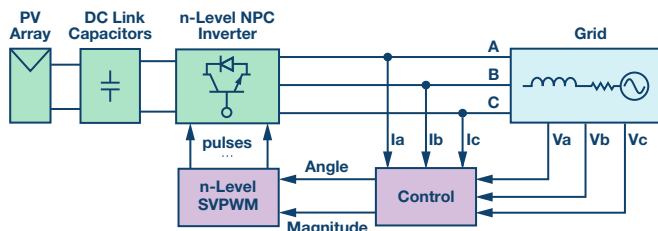


Figure 5. Generalized SVPWM control method for the NPC topology.

There are many types of control methods that can be implemented to operate an inverter system comprised of the multilevel SVPWM and the NPC. Thus, due to the wide spectrum of control methods that can be applied to an inverter, the technique must be chosen to best suit the system application.

For exhibiting improved grid parameters regarding photovoltaic systems generating and injecting energy into the grid, the reactive power control is very suitable for 3-phase grid-connected PV inverters. This control method allows the system to control the dc power generated by the PV system, the transference of this electrical energy to the grid, and to control the active and reactive powers in order to reduce losses in the reactive part of the system. Moreover, as the motor drive control is similar to the control of an inverter, techniques used on ac induction motor drives can be adapted to PV inverters. In this way, the field oriented control (FOC) technique, or vector control, which operates by controlling the

frequency, amplitude, and phase of the motor drive, can be adapted and implemented in a PV converter connected to the electric distribution network. This method controls the generated currents' frequency, amplitude and phase angle, where this information are used to generate the SVPWM pulses that control the power inverter. It also has several other advantages—for instance, lower power consumption, higher efficiency, and lower operating and component costs.

Therefore, both methods can be combined and implemented on a PV multilevel diode NPC inverter with multilevel SVPWM to maximize the system's performance. In this way, the implementation of this method to control the 3-phase multilevel diode NPC inverter in a closed-loop fashion while connected to the electrical grid is as follows:

- ▶ First of all, the vector control method gets as inputs the 3-phase grid phase voltages and the Phase A phase angle.
- ▶ These 3-phase voltages are then converted into a 2-axis system through an alpha-beta-zero transformation.
- ▶ Using the measured phase angle in a d-q-0 transformation, the 2-axis coordinate system is rotated and aligned with this angle information.
- ▶ In the meantime, the control method also uses the 3-phase generated currents applying the alpha-beta-zero and d-q-0, which uses the reference angle information to transform them.
- ▶ After both the generated and reference signals are transformed, the technique generates error signals by subtracting one signal from another. Also, in order to improve the system's stability, the error signals must go through classic proportional-integral (PI) control loops.

- ▶ From this point, the system transforms the error signal originated in the PI controller from the synchronous reference frame, the d-q-0 frame, to the stationary reference frame, the alpha-beta-zero frame. This step predicts the amount of error generated between the current voltage vector and the next voltage vector.
- ▶ The two past steps eliminate, or control, the quadrature voltage, the q component, from the d-q-0 transform, which represents the reactive power component in the system.
- ▶ Then, the alpha and beta components from the alpha-beta-zero transform go through a Cartesian to polar transform, yielding the magnitude and angle.
- ▶ Finally, using the magnitude and angle information, the SVPWM calculates the reference vector, the region and sector in which this vector is located, the voltage vectors that comprise that area, the dwelling time for the switches, and, lastly, the optimal switching sequence for the inverter. These are transmitted as pulses that drive the converter, generating the desired voltage and current values in the system.

A phase-locked loop (PLL) can be implemented to extract the angle information from Phase A to perform the coordinate transformation, transforming the system to be adaptive to variations of the frequency in the input signals.

Control Method Implementation with Positive-Sequence Voltage Detector

In addition to the aforementioned frequency adaptive control method being implemented, a positive-sequence voltage detector (PSD) connected to the grid can be used to improve the method. This can be used in order to detect further grid fault conditions, such as unbalanced and distorted grid circumstances, and to adapt the system to it—thus reducing losses and improving the system's efficiency.

Moreover, it is fundamental to control the power exchange between the inverter and the grid without tripping the converter's protections, permitting the ride through of the transient fault and keeping the system according to the grid connection standards.

Therefore, with the purpose of achieving a fast and precise detection of the grid under unbalanced, distorted, and unstable conditions, two other blocks must be added to the system, these being the quadrature-signal

generator (QSG) implemented with a second-order generalized integrator (SOGI), which brings harmonic blocking capability to the system and the positive-sequence calculator (PSC). This system is usually implemented in conjunction with a PLL. However, as it is already in use in the d-q-0 transformation, another PLL will not be required in the system, and the information of the existing PLL can be used.

In this way, the 3-phase grid voltages on the alpha-beta reference frames are filtered by the QSG, rendering 90° shifted components of the original alpha-beta voltages. Then, these signals go through the PSC, which uses the instantaneous symmetrical components to successfully detect the positive-sequence components on the alpha-beta-zero voltages. At length, the transformed positive-sequence components go through the d-q-0 transformation, which uses the PLL angle information employed in the previous iteration to maintain the system frequency and phase adaptive, generating the d-q-0 components.

After completing the entire process to acquire and transform the positive-sequence components from the grid's voltage, the system continues as described before. These components are subtracted from the generated currents and then go through the PI control loop following the method described before.

Therefore, although the system still performs the same steps as the control method presented before, the system now has an adaptive reaction to unbalanced and distorted grid conditions.

Simulation in the Simulink Environment

The system can be successfully simulated in the Simulink environment. The full system comprises a grid connected multilevel diode NPC inverter topology controlled by a multilevel SVPWM technique and a closed-loop reactive power control method adapted into a FOC technique, implemented with a positive-sequence detector.

The simulation shows that the system presented stability in the case of large grid impedance variations, ride through grid voltage disturbances, adaptation to grid voltage variations, and operation at the unity power factor as required by standards.

While designing the system, some additional parameters, such as switching frequency, distortion, losses, harmonic generation, and speed of response, have to be heavily considered regarding modulation strategies.

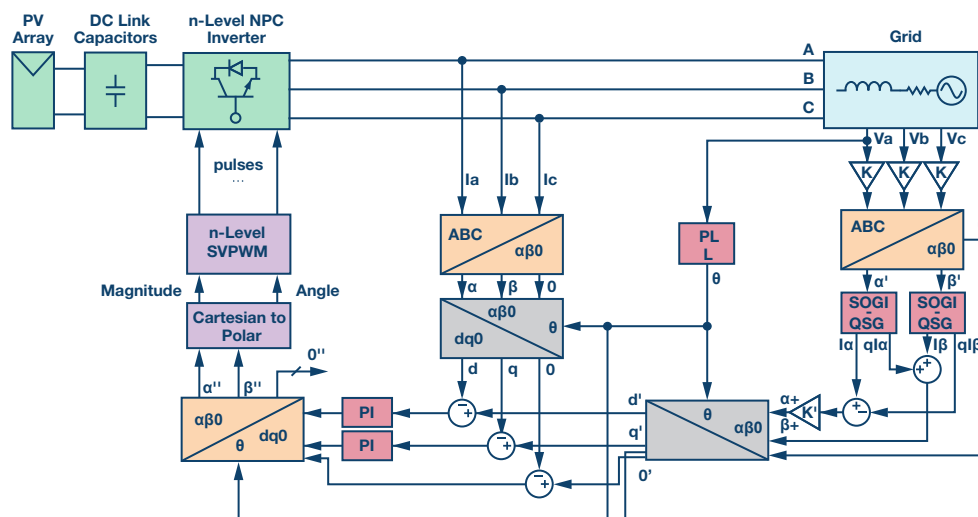


Figure 6. Complete control method for multilevel diode NPC and SVPWM implemented with PSD.

The figures below demonstrate the performance of the system. In the simulation, the grid begins as fully functional while the system has to be turned on at 0.0 sec. When the simulation reaches 0.06 sec, which represents three full periods of the grid voltage, thus the system is already stable, there are drops in each grid voltage, and it lasts for 0.04 sec, returning to normal after 0.1 sec of simulation.

Therefore, the results without the PSD implementation demonstrates good performance before the grid failure, which represents a big voltage drop in the system and an unbalance situation in the generated currents. The figure with PSD roughly takes one period to stabilize, 0.02 sec, but when exposed to faulty grid conditions, it adapts better than the system without the PSD, demonstrating fully balanced generated currents. Besides, when the system reaches 0.18 sec, it is requested to be turned off, so, the middle switches of the diode NPC are then open, interrupting any current generation, with exception of a brief period where the capacitors and inductors are discharged.

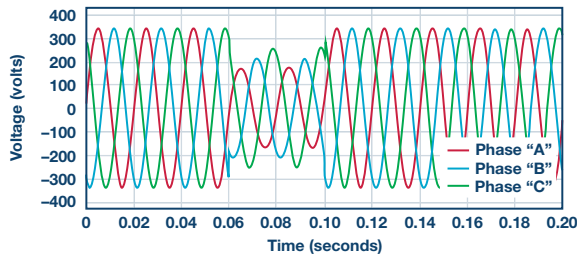


Figure 7. 3-phase grid voltages.

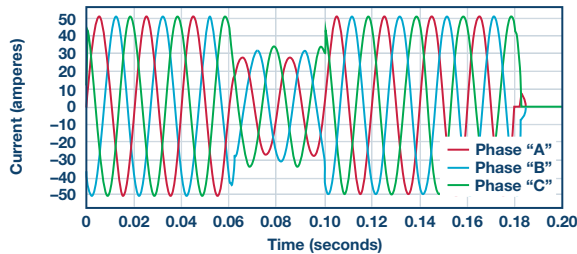


Figure 8. 3-phase, five-level generated currents without PSD implementation.

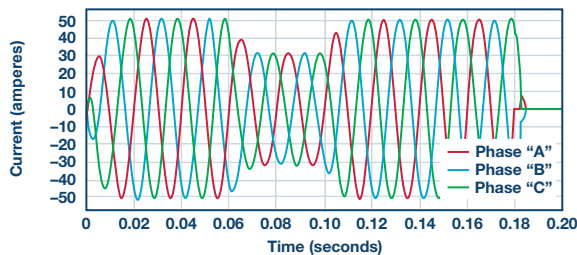


Figure 9. 3-phase, five-level generated currents with PSD implementation.

The SVPWM pulses that are modulating the inverter's Phase A are presented below; the NPC switches at 100 kHz. The switching frequency of the NPC can be easily selected, and the system operates satisfactorily at a very wide range of frequency values, from 20 kHz to 300 kHz.

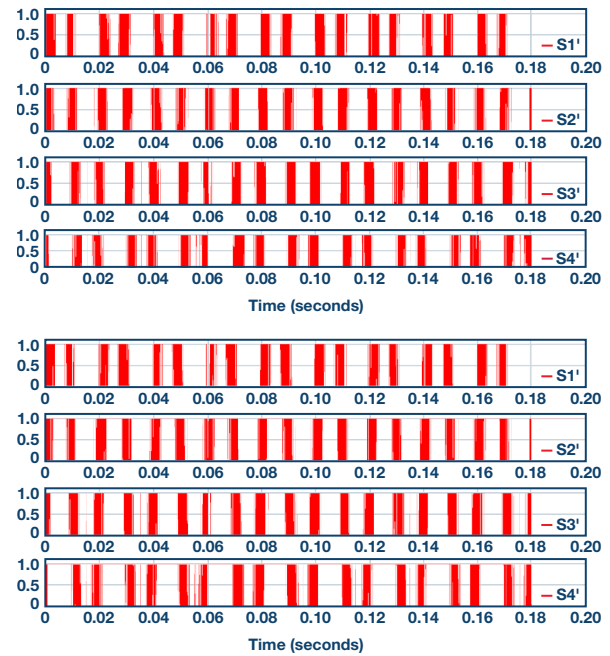


Figure 10. Five-level, Phase A switching pulses.

Hence, the results show that the system has several advantages over other methods and can be implemented in several ways, such as increasing its number of levels, implementing grid fault adaptive systems, more complex control methods, and employing faster power control loops. Thus, rendering more efficient, less expensive, smaller, and more intelligent systems for the modern world.

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