**AKAGI, Hirofumi: "Establishment of Mathematical Formulation of Three-Phase Power Components, and Pioneering Research on Semiconductor-Based Power Conversion Systems"**

## 1. Biography and Awards/Recognition

AKAGI, Hirofumi

Akagi was born in Okayama, Japan, in August 1951. He received his B. S. degree in electrical engineering from the Nagoya Institute of Technology in 1974, and his M. S. and Ph. D. degrees in electrical engineering from the Tokyo Institute of Technology in 1976 and 1979, respectively. He joined the Nagaoka University of Technology as Assistant Professor in the department of electrical engineering in April 1979. Then, he was promoted to Associate professor in 1984. He stayed the Massachusetts Institute of Technology (MIT) as Visiting Research Scientist for ten months in 1987. He moved to Okayama University as Professor in the department of electrical and electronic engineering in 1991. He stayed the University of Wisconsin at Madison as Visiting Professor for three months, and then the MIT as Visiting Professor for three months in 1996. He came back to the Tokyo Institute of Technology as Professor in the department of electrical and electronic engineering in 2000. Since 2017, he has been working for the Tokyo Institute of Technology as Specially-Appointed Professor and Emeritus Professor.

Akagi has received many awards and recognition, mainly from the Institute of Electrical and Electrical Engineers (IEEE). He is the recipient of six IEEE Transactions Prize Paper Awards in 1991, 1999, 2003, 2004, 2009, and 2013. He was elected as an IEEE Fellow in 1996 and an IEEE Life Fellow in 2020. He is the recipient of the 2001 IEEE Power Electronics Society William E. Newell Award, the 2004 IEEE Industry Applications Society Outstanding Achievement Award, the 2008 IEEE Richard Harold Kaufmann Award, the 2012 IEEE Power & Energy Society Nari Hingorani Custom Power Award, and the 2018 IEEE Medal in Power Engineering. He received the 2020 Gaston Maggetto Medal from the European Power Electronics and Drives Association (EPE).

In addition, Akagi has received the following domestic awards and recognition. He received five IEEJ (the Institute of Electrical Engineers of Japan) Transactions Prize Paper Awards in 1984, 1997, 2005, and 2007. He is the recipient of the 2012 IEEJ Industry Applications Society Shota Miyairi Outstanding Achievement Award. He was elected as an IEEJ Fellow in 2013, and an IEEJ Life Fellow in 2020. He received the 2008 Science and Technology Award in research from the Ministry of Education, Culture, Sports, and Science and Technology (MEXT). He was recognized as a recipient of "*One Step on Electro-Technology – Look Back to the Future –*" with different citations in 2020 and 2022 from the IEEJ, where this prestigious recognition is similar in concept and purpose to the "IEEE Milestones." He is the inaugural recipient of the 2021 Hirose Prize from the Hirose Foundation.

## 2. Semiconductor-Based Power Conversion and Overview of Akagi's Research

Semiconductor devices such as diodes and transistors can be divided into the following two groups in terms of application; for signal processing and for power conversion or power processing. The former has been used widely to electronic produces and control equipment, presently as a form of large-scale integrated circuits (LSIs) including the latest digital signal processors (DSPs), field programable gate arrays (FPGAs), and so on. As for the latter, the IEEJ has recommended scientists and engineers to use a technical term "power semiconductor devices" or shortly "power devices." The power (semiconductor) devices have been used for various fields, from information and communications products as well as home appliance, to industry, transportation, and electric power utility, all of which have been supporting human life and social infrastructure. Their output power ranges from several watts to several gigawatts, and their frequency ranges from zero (dc) to 13.56 MHz. Both power and frequency are equally important in applications of power semiconductor devices to power conversion or power processing, while frequency would be more important than power in their applications to signal processing in many cases.

Power electronics and semiconductor-based power conversion are often used as a synonymous term. Research scientists and engineers in the field of power electronics can be categorized into those doing research on power semiconductor materials and/or devices, and those on power conversion circuits and systems. Akagi has been doing and conducting theoretical and experimental research on high-power conversion systems and applications, with a close relation to the power electronic industry, aiming at long-term research looking ahead ten years. He used in his research Silicon-based power semiconductor devices such as diodes, thyristors, bipolar junction transistors, static induction transistors, MOSFETs, and insulated-gate bipolar transistors (IGBTs). Recently, he has paid much attention to research on the 750-V 100-kW 16-kHz bidirectional isolated dual-active-bridge (DAB) dc-dc converters using the latest Silicon-Carbide MOSFETs available on the market. He has published pioneering papers on power conversion systems on theory, circuit, control, and application. According to *Google Scholar,* his lifetime publications have been cited more than 61,000 times with an h-index of 102. He received the 2018 IEEE Medal in Power Engineering and the 2022 EPE Gaston Maggetto Medal. He is the world's only winner of both IEEE and EPE Medals at present.

One of the most well-known research contributions is to have established and presented theory of three-phase power components, or the "*pq* theory," in 1983. Since then, power electronics experts have recognized and admired it as "proposal of a new concept, and establishment of a new theory," thus leading to many awards and recognition as shown in section 1. The late Dr. Shota Miyairi, Professor Emeritus at the Tokyo Institute of Technology, left the following words in [1]: "Technological originality will disappear with technical advances, whereas scientific originality will continue remaining." Whether or not Akagi's *pq* theory belongs to scientific originality will be judged by power electronics experts 60 years from now, or 100 years after the emergence of the *pq* theory in 1983.

## 3. Why did Akagi Jump in Research on Semiconductor-Based Power Conversion?

Akagi was born and grew up in Okayama. After he graduated from a public senior high school, he was enrolled in the Nagoya Institute of Technology, majoring electrical engineering. He enjoyed studying power conversion, electric machine, control theory, and power systems, all of which are related to electric power and energy. He was the most interested in the latest power conversion technology at that time, which allowed silicon semiconductors to control a torque of a dc motor for the Japanese high-speed bullet train and commuter trains at that time. Since he became a senior undergraduate student at the beginning of April 1973, he has been doing, and then, conducting theoretical and experimental research on a broad range of semiconductor-based power conversion circuits, systems, and applications.

## 4. Theory of Instantaneous-Power Components in Three-Phase Circuits, or the *pq* Theory

### 4.1. Background

A course subject "electric circuit theory," or something like that, is mandatory for undergraduate students who are majoring electrical engineering at universities and technical colleges not only in Japan but also in the world. Professors or instructors teach the concept of a pair of active power and reactive power, in which the waveforms of voltage and current in single-phase circuits are assumed to be sinusoidal under steady-state conditions. This assumption makes it possible to formulate the reactive power in a single-phase circuit. This formulation is expanded directly into a three-phase circuit that is considered as a set of three independent single-phase circuits.

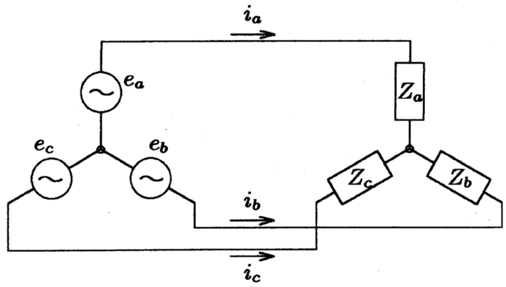


Fig. 1. Three-phase three-wire alternating current (ac) circuit.

In the 1970s, power electronics experts in the world actively tried to define and formulate "instantaneous reactive power" in a single-phase circuit under an assumption of a sinusoidal waveform of voltage. However, their definitions and formulations required many actual values of current, not only at present, but also in the past because they were based on a mathematical concept of a time average over an interval of time or a time window, say, a line cycle, half the line cycle, or another specific short interval of time. This requirement concluded that the instantaneous reactive power defined in a single-phase circuit would be no longer "instantaneous," strictly speaking. In addition, the requirement made the resultant values variant or inaccurate because the values depended strongly on the time window, especially when the waveform of current is distorted, aperiodic, and/or changing randomly. Power electronics experts were struggling to solve the above-mentioned issues and conflicts. However, no one had succeeded in establishing any theory convincing themselves.

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Eq. 1. The αβ transformation of three-phase voltages and currents.

Akagi, thinking reverse, began with three-phase circuits to present a new theory in 1983 [2], which is now referred to as the "*pq* theory" amongst power electronics experts in the world, as described in the next subsection.

### 4.2. The *pq* Theory and Physical Meanings of the Power Components

Fig. 1 shows a three-phase three-wire ac circuit, in which the summation of the three-phase currents is always zero; $i_a + i_b + i_c = 0$. This relation reduces the number of the independent currents from three to two. Akagi applied the αβ transformation given by equation (1) to three-phase voltages and currents without zero-sequence voltage or current components.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

Eq. 2. Formulation of *p* and *q*.

Then, he defined the instantaneous real power *p* and the instantaneous imaginary power *q*, as formulated by equation (2). What is the most important and interesting in equation (2) is that the determinant of the two-dimensional matrix is always a positive number, except for the condition of $e_\alpha = e_\beta = 0$. Note that the dimension of *p* is [W] without any doubt, whereas that of *q* is neither [VA] nor [var]. Therefore, a new dimension should be introduced to *q*. However, it has not yet been determined internationally.

Next, he defined and formulated the instantaneous active-power and reactive-power components in the α phase and those in the β phase. The following relations among the four power components come into existence:

1) The sum of the instantaneous active-power component in the α phase and that in the β phase is always equal to the instantaneous real power *p*.
2) The sum of the instantaneous reactive-power component in the α phase and that in the β phase is always equal to zero.

Akagi gave a mathematical proof to the above two relations, thus resulting in making a clear physical explanation of the instantaneous reactive-power component in the α phase and that in the β phase [2]-[4]. Both definition and formulation, as well as the physical meaning, were consistent with speculation, thus promoting power electronics experts to accept the theory as valid. Recently, the experts around the world have referred to Akagi's theory as the "*pq* theory." According to *Google Scholar*, references [2] to [4] have been cited more than 9,700 times in total.

### 4.3. Contributions to Academia and Education

Jacques L. Willems, who is Professor at the University of Gent in Belgium, introduced a technical term "the Akagi-Nabae Power Components" to the title of his IEEE Transactions paper, and expanded the *pq* theory into general multi-phase systems with more than three phases [5]. At present, many universities in the world teach the "*pq* theory" as a fundamental theory in three-phase circuits to graduate students majoring power systems and power electronics.

## 5. Three-level Neutral-Point-Clamped (NPC) Inverters

### 5.1. Background

Since the early 1960s, the continuous development of power devices has spurred power electronics experts to do research on power conversion systems and their applications. The bipolar junction transistors (BJTs) rated at 500 V and 50 A were available from the market in the late 1970s. The experts were allowed to use the BJTs as on/off switching devices, making it easy to design and build a three-phase voltage-source PWM inverter using the six BJTs. Note that a free-wheeling diode rated at 500 V and 50 A was connected in anti-parallel with each BJT. The use of this inverter brought an adjustable-speed drive to a three-phase 200-V induction motor. However, it was impossible to apply the inverter to three-phase 400-V induction motors from lack of voltage-blocking capability of the BJTs. Series connection of the two 500-V BJTs per arm was able to solve the problem. However, the following serious technical problem came across: How to realize simultaneous on/off switching of the two series-connected BJTs under the existence of unavoidable mismatches in electric characteristics of the BJTs. Unfortunately, these mismatches were inevitable because they resulted from semiconductor production processes.

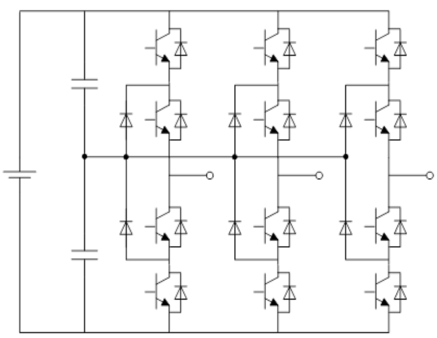

Fig. 2. Original three-phase three-level NPC inverter.

### 5.2. Three-Phase Three-Level NPC Inverters and its World's First Verification

Nabae, Takahashi, and Akagi, who were working for the Nagaoka University of Technology at that time, presented a short Japanese paper at the IEEJ Annual Conference in March 1980, followed by its full English paper published in the IEEE Transactions in 1981 [9]. This IEEE paper described two types of three-phase three-level neutral-point-clamped (NPC) inverter circuits: One was the original, and the other was derived from the original.

Fig. 2 shows the original inverter circuit. A downscaled prototype of the original three-phase three-level NPC inverter was designed and built to verify its validity and effectiveness for an adjustable-speed drive of the three-phase

200-V, 2.2-kW, 50-Hz induction motor [9].

Fig. 3 shows a snapshot of waveforms of voltage and current at the ac side of the original three-phase three-level NPC inverter when the motor was operated at the rated voltage, frequency, and power. This inverter provides the following distinct advantages:

1) No simultaneous on/off switching is required for the two series-connected BJTs per arm at any time. In other words, each arm is free from simultaneous on/off switching.
2) This three-phase NPC inverter produces a three-level waveform of voltage in phase-to-neutral and a five-level waveform in phase-to-phase at the side. The three-level inverter make motor torque ripples lower than does a traditional two-level inverter with the same dc input voltage.
3) All the power semiconductor devices consisting of 12 BJTs, 12 free-wheeling diodes, and six clamping diodes are characterized by having the same voltage rating. This advantage makes it easy for design engineers to select and purchase the power semiconductor devices available from the market.

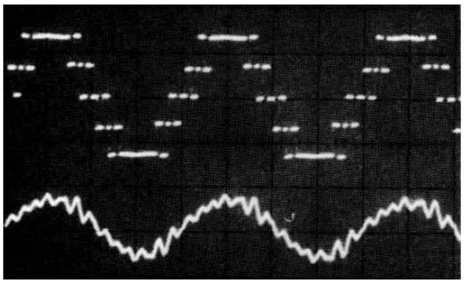

Fig. 3. Experimental waveforms.
upper: phase-to-phase voltage (200 V/div)
lower: motor current (20 A/div, 5 ms/div)

Fig. 4 shows the other inverter circuit derived from Fig. 2. Although the two inverter circuits are slightly different in configuration, the two are the same in operating principle, and the same in waveforms of voltage and current at their ac side, except for a short interval of time, which is equivalent to the so-called "dead time" in a traditional two-level inverter. According to *Google Scholar*, the IEEE Transactions paper [9] is cited more than 6,500 times at present, and it is still counting although the IEEE paper was published in 1981.

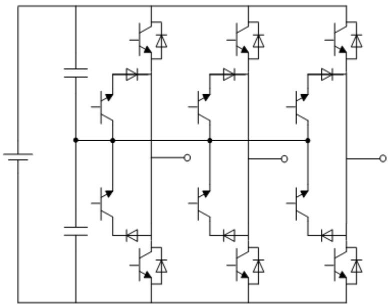

Fig. 4. Three-phase three-level NPC inverter derived from Fig. 2.

## 5.3. Application Examples of the Original and Derived Three-Level NPC Inverters

It took 12 years to put the original NPC inverter into practical use after publication of [9]. It is an extremely short period of time in this field. On the other hand, it took more than 26 years to commercialize the derived NPC inverter.

### 1) Application to Steel-Mill Main Motor Drives

Around 1990, Japanese companies succeeded in developing the gate-turn-off thyristor (GTO) rated at 4.5 kV and 4 kA for the first time in the world. In 1993, a Japanese manufacturer commercialized the original three-phase three-level NPC inverter rated at 4 MVA for steel-mill main motor drives, in which the latest digital controller at that time played an important role in putting the NPC inverter into practical use. Around 1995, the Japanese manufacture developed and put the 10-MVA (with an overrating of 15 MVA) inverter using the GTOs rated at 6 kV and 6 kA into practical use for steel-mill main motor drives. Nowadays, overseas manufacturers commercialize the original NPC inverters shown in Fig. 2 for steel-mill motor drives and other medium-voltage industrial motor drives [10].

### 2) Application to Japanese High-Speed Bullet Trains or the "Shinkansen"

In the late 1990s, Japanese companies developed the 3.3-kV insulated-gate bipolar transistor (IGBT) that was lower in gate-drive power, higher in switching frequency, and easier in device packaging and assembling than the 3.3-kV GTO. Japanese two railway companies and four manufacturers promoted research and development for introducing the original three-level NPC inverter using 3.3-kV IGBTs to Japanese high-speed bullet trains. Since March 1999, the JR Central has been putting the original NPC inverters into commercial operation for driving traction induction motors from series 700 to the latest N700S high-speed bullet trains. The JR East also has been using the original NPC inverters for series E2 (partially since 1997) and E4 to the latest E7 high-speed bullet trains. [10].

### 3) Application to Large-Scale Photovoltaic Systems

The emergence of the 1.2-kV trench-gate IGBT around 2005 urged Japanese manufactures to put the derived three-phase three-level NPC inverter shown in Fig. 4 into practical use as a three-phase grid-tied inverter for large-scale photovoltaic systems. This world' first success has made overseas manufactures follow the Japanese ones. The global spread of the derived NPC inverter results in making the market bigger year by year at a world level.

At present, the *pq* theory has been applied not only to system/control designs of the photovoltaic systems but also to almost all three-phase grid-tied converters and inverters, irrespective of 2-level, 3-level, or any-level ones.

## 6. Research Contributions to the Power Electronics Academia and Industry

Semiconductor-based power conversion can be divided mainly into theoretical research and experimental research.

Akagi's theoretical-research contributions are limited to the *pq* theory described in section 4 [2]-[4], and a mathematical proof, as well as its experimental verification, on equivalence in harmonics between a cycloconverter and a thyristor bridge converter [11]. A small number of theoretical papers have been presented or published in the field of power electronics, even in the world. Research and practical engineers in the power electronics industry around the world has applied the *pq* theory directly or indirectly to system/control designs of pure/hybrid active filters for power conditioning [6], static synchronous compensators (STATCOMs) [7]-[8], and so on.

Akagi's experimental-research contributions include the world's first practical pure/hybrid active filters for power conditioning [6], the three-phase three-level NPC inverters described in section 5 [9]-[10], high-frequency induction heating systems [12], high-frequency corona discharge processes [13], a practical mitigating technique of electromagnetic interference in an inverter-driven motor [14], multilevel converters [15], bidirectional isolated dual-active-bridge (DAB) dc-dc converters [16], real-time real-power emulators for medium-voltage high-power motor drive systems [17], and so on. The common thought going through with the above various research projects was to combine the latest power semiconductor devices at that time with novelty, originality, and/or usefulness in configuration, control, or application. Akagi conducted collaborative research with the power electronics industry on the above research projects, thus leading to prompt practical applications of his research achievements.

Last but not least, some of recently-published Japanese or English textbooks on power electronics for undergraduate and graduate students have described the *pq* theory and/or the three-phase three-level NPC inverters. This publication would make Akagi happy and honorable as a university professor.

## 7. References


[1] S. Miyairi, "Power electronics: Retrospect over 30 years and prospect (invited paper)," *Proceedings of the Power Electronics Society,* vol. 15, pp. 1-6, 1989 (in Japanese).

[2] H. Akagi, Y. Kanazawa, and A. Nabae, "Generalized theory of the instantaneous reactive power in three-phase circuits," *IEEJ International Power Electronics Conference* (*IPEC-Tokyo*), pp. 1375-1386, March 1983.

[3] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components," *IEEE Trans. on Industry Applications*, vol. 20, no. 3, pp. 625-630, May 1984.

[4] H. Akagi, E. H. Watanabe, and M. Aredes, "*Instantaneous power theory and applications to power conditioning*," IEEE Press and Wiley, 379 pages for the first edition in 2007, and 450 pages for the second edition in 2017.

[5] J. L. Willems, "A new interpretation of the Akagi-Nabae power components for non-sinusoidal three-phase situations," *IEEE Trans. on Instrumentation and Measurement*, vol. 41, no. 4, pp. 523-527, Aug. 1992.

[6] H. Akagi, "Active harmonic filters (invited paper)," *Proceedings of the IEEE*, vol. 93, no. 12, pp. 2128-2141, Dec. 2005.

[7] A. Iizuka, M. Kishida, Y. Mochinaga, T. Uzuki, K. Hirakawa, F. Aoyama, and T. Masuyama, "Self-commutated static var generator at Shintakatsuki substation," *IEEJ IPEC-Yokohama*, pp. 609-614, April 1995.

[8] K. Masaki, K. Temma, H. Harada, Matsuda, and N. Morishima, "Enhancement of steady-state stability and suppression of overvoltage using 450-MVA GCT-STATCOM," *Mitsubishi Electric Review,* vol. 87, no. 11, pp. 656-669, Nov. 2013. (in Japanese)

[9] A. Nabae, I. Takahashi, and H. Akagi, "A new neutral-point-clamped PWM inverter," *IEEE Trans. on Industry Applications*, vol. 17, no. 5, pp. 518-523, Sep. 1981.

[10] H. Akagi, Y. Akita, I. Aoyama, T. Tanaka, Y. Okuma, and S. Tamai, "Emerge and application of three-level neutral-point-clamped (NPC) inverters (invited paper)," *IEEJ Workshop on Electro-Technology History,* HEE-20-010, pp. 7-12, Aug. 2020. (in Japanese)

[11] S. Miyairi, H. Akagi, T. Fukao, and M. Fujita, "Equivalence in harmonics between cycloconverters and bridge converters," *IEEE Trans. on Industry Applications*, vol. 15, no. 1, pp. 92-99, Jan 1979.

[12] H. Akagi, T. Sawaei, and A. Nabae, "130-kHz 7.5-kW current-source inverters using static induction transistors for induction heating applications," *IEEE Trans. on Power Electronics*, vol. 3, no. 3, pp. 303-309, May 1988.

[13] H. Fujita and H. Akagi, "Control and performance of a pulse-density-modulated series-resonant inverter for corona discharge processes," *IEEE Trans. on Industry Applications*, vol. 35, no. 3, pp. 621-627, May 1999.

[14] H. Akagi and T. Doumoto, "An approach to eliminating high-frequency shaft voltage and ground leakage current from an inverter-driven motor," *IEEE Trans. on Industry Applications*, vol. 40, no. 4, pp. 1162-1169, July 2004.

[15] H. Akagi, "Multilevel converters: Fundamental circuits and systems (invited paper)," *Proceedings of the IEEE*, vol. 105, no. 11, pp. 2048-2065, Nov. 2017.

[16] R. Haneda and H. Akagi, "Design and performance of the 850-V 100-kW 16-kHz bidirectional isolated DC-DC converter using SiC-MOSFET/SBD H-bridge modules," *IEEE Trans. on Power Electronics*, vol. 35, no. 10, pp. 10013-10025, Oct. 2020.

[17] K. Saito and H. Akagi, "A real-time real-power emulator for a medium-voltage high-speed electrical drives: Discussion on mechanical vibrations," *IEEE Trans. on Industry Applications*, vol. 57, no. 2, pp. 1482-1494, March 2021.