

Novel ZCS-PFM Series Resonant High Frequency Inverter for Electromagnetic Induction Eddy Current-Heated Roller

Sang-Pil Mun* · Shin-Chul Kang · Soo-Wook Kim · Mutsuo Nakaoka

Abstract

This paper presents a novel prototype of zero current switching pulse frequency modulation (ZCS-PFM) high frequency series resonant inverter using IGBT power module for electromagnetic induction eddy current heated roller in copy and printing machines. The operating principle and unique features of this voltage-fed half bridge inverter with two additional soft commutation inductor snubber are presented including the transformer modeling of induction heated rolling drum. This soft switching inverter can achieve stable zero current soft commutation under a discontinuous and continuous resonant load current for a widely specified power regulation processing. The experimental results and computer-aided analysis of this inverter are discussed from a practical point of view.

Key Words : ZCS-PFM High Frequency, Half Bridge Inverter, Induction Eddy Current-Heated Roller

1. Introduction

In recent years, the global warming due to a great consumption of electrical energy becomes a social serious problem from an environmental point of view. In office automation fields, the copy machine is widely used together with information and telecommunication electronics appliances. With the increase of the interest to worldwide global environment, the energy saving power electronics regulation technology has also

attracted special interest in office automation field [1]. In the laser printer, after its toner is processed for copying paper, the process supplying a heat to the toner for fixing is indispensable for copying machine. At present, most of system in which the toner is designed to fix using the halogen heated fixing scheme is conventionally introduced in the copy machines [2]. However, there are some problems to be solved such as heating speed, a lot of energy consumption for this consumer application[3-5].

In this paper, a high frequency inverter type electromagnetic induction heated (IH) roller for toner fixing process is proposed in place of the conventional halogen heater type, which is based on eddy current induced in the cylindrical

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rolling drum. The induction heating technology has widely applied in home electronic and household appliances such as electro-magnetic induction heated cooker and hot water producer, since it has some remarkable advantages such as clean, rapid heating, temperature control easiness and efficient energy conversion. Therefore, the electromagnetic induction heated processing scheme is actively considered for the high frequency inverter type induction heated rolling drum in copy machine. A voltage source lossless inductor assisted half bridge zero current soft switching high frequency inverter with PFM control scheme for commercial utility power supply 200[Vrms] is implemented for this application, and its operation principle and performances are originally evaluated and discussed for induction heated roller drum in the copy machine. In the first place, the induction heated roller load of high frequency load resonant inverter is represented using a magnetic flux based transformer circuit model, and the computer aided simulation analysis of this inverter is developed including circuit parameter measurement. In the second place, it is verified that the proposed high frequency ZCS-PFM inverter such as the voltage source series resonant inverter circuit topologies; half bridge type, center tapped type, full bridge type and boost half bridge type have particular effectiveness and practicability for toner fixing processing from an experimental point of view. Finally, the operating principle is described and the operating performances is evaluated and discussed on the basis of simulation and experiment.

2. Proposed ZCS-PFM Controlled High Frequency Inverter

2.1 Induction Heating Load Technology

The induction heating of conductive metal and semiconductor materials is based on non-contact direct heating using the electromagnetic eddy current induction principle.

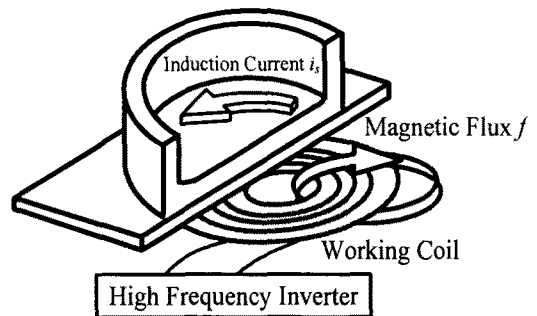


Fig. 1. Induction heating principle

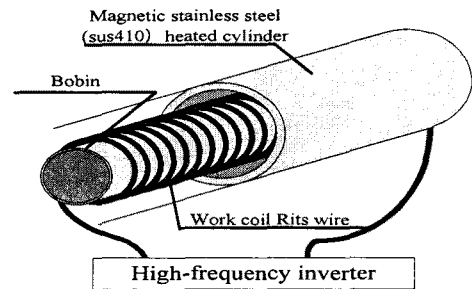


Fig. 2. Induction heating roller with working coil

Fig. 1 shows a basic principle of electromagnetic induction heated cooking appliances with a pancake type spiral planer coil as litz wire based working coil for generating high frequency magnetic flux. The pancake type working coil (see Fig. 1) connected the quasi-resonant zero voltage soft switching high frequency inverter using IGBTs generates high frequency magnetic flux. And then, high-frequency magnetic field produced from the working coil makes eddy current in the

bottom portion of vessel or pan.

As a result, in principle, the bottom portion of this vessel is able to be directly heated on the basis of Joule’s law. The Joule’s heat is to be specified by resistivity of the vessel material due to eddy current heating. The electromagnetic eddy-current induction heating has excellent unique features such as rapid heating, clean, local part heating and safety. In this paper, induction heating roller drum load composed of litz wire based cylindrical type working coil and cylindrical heating element depicted in Fig. 2 is newly used for a load of the inverter.

Fig. 3 shows the structure of heating roller load as a load of this high frequency inverter. In the copy and print machine, toner image adheres to decalomania paper in the unstable condition, after decalomania paper separates from the photodetector.

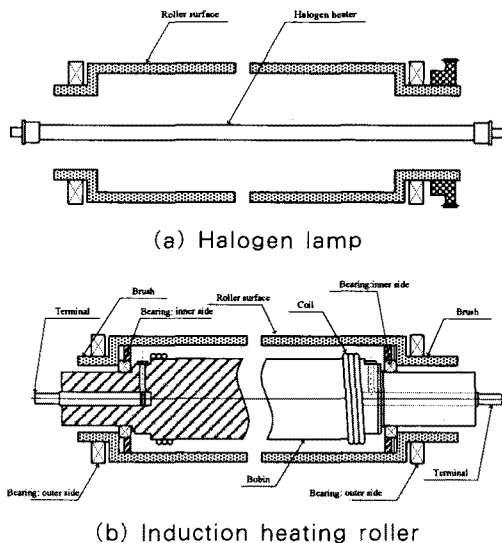


Fig. 3. Sectional view of fixing roller

This toner image is dried by the fixing equipment in which the heating roller consists of the working coil and the fixing roller, and toner

image becomes an eternal image. At present, the fixing equipment widely spreads from the low speed to high-speed copy machine and color copy machine for industrial use is heat fixing system, and also halogen lamp system in Fig. 3 (a) is introduced in conventional copy machine. The induction heating roller drum which Fig. 3 (b) demonstrates is newly adopted as induction heat fixing roller equipment.

2.2 Equivalent Transformer Model of Induction Heating Load

The equivalent electrical model of the IH load can be represented as a transformer shown in Fig. 4 Here L_1 is a self inductance of the working coil, which is defined by the high frequency magnetic flux caused by inverters current, R_2 is a frequency dependent resistance of the roller caused by the skin effect. The inductance of the transformers second side and mutual inductance are defined as L_2 and M , respectively.

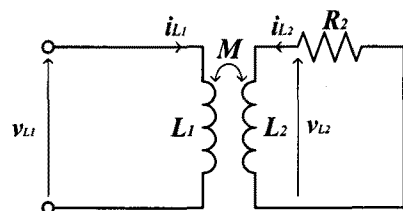


Fig. 4. Transformer model of induction heating load

If the internal resistance of the working coil is neglected, circuit equations can be derived as

$$\begin{cases} j\omega L_1 I_{L1} + j\omega M I_{L2} = V_{L1} \\ j\omega M I_{L1} + (j\omega L_2 + R_2) I_{L2} = 0 \end{cases} \quad (1)$$

After simple transformations, equation (2) can be obtained

$$\frac{V_{L1}}{I_{L1}} = \frac{\omega^2 M^2 R_2}{R_2^2 + \omega^2 L_2^2} + j\omega \frac{L_1 R_2^2 + \omega^2 L_2 (L_1 L_2 - M^2)}{R_2^2 + \omega^2 L_2^2} \quad (2)$$

If the first term of equations (2) is considered as R_a and the factor of the second $j\omega$ is represented as L_a , then L_a and R_a can be given by

$$\begin{cases} R_a = \frac{\omega^2 M^2 R_2}{R_2^2 + \omega^2 L_2^2} \\ L_a = L_1 - \frac{\omega^2 L_2 M^2}{R_2^2 + \omega^2 L_2^2} \end{cases} \quad (3)$$

As a result, the transformer model of the induction heating load shown in Fig. 4 can be represented by R_a - L_a parameters that can be measured experimentally.

For the load shown in Fig. 2, such parameters as transformers electromagnetic mutual coupling coefficient k and time constant of the IH load τ can be defined as ;

$$\begin{cases} k = \frac{M}{\sqrt{L_1 L_2}} \\ \tau = \frac{L_2}{R_2} \end{cases} \quad (4)$$

If time constant τ of the IH load is constant, the circuit behavior of the IH load is the same for any value L_2 and R_2 . Therefore, it is better to represent the IH load by using new parameters L_1 , k and τ defined as (4) rather than using the circuit parameters of the equivalent transformer circuit depicted in Fig. 3, where L_1 is measurable and L_2 , M and R_2 cannot be measured. If k and τ from (4) are represented by measurable parameters R_a , L_a and L_1 , it become simple to analyze the operation of the inverter circuit with the IH load.

2.3 System Description & Circuits Operation

The proposed lossless inductor snubber-assisted high frequency ZCS inverter using IGBT power module is depicted in Fig. 5. The series resonant capacitors C_1 and C_2 are used for the series compensation resonant capacitors, and two loss less inductor snubbers; L_{s1} and L_{s2} are respectively connected in series with the active power switching blocks; $Q_1(S_1/D_1)$ and $Q_2(S_2/D_2)$. Timing sequences of the gate voltage pulse signals supplied to two active power switches ; Q_1 and Q_2 for driving the high frequency inverter is shown in Fig. 6. It is possible that its output power can be continuously adjusted by varying switching frequency under a condition of fixed on-time ; $T_{on1}=T_{on2}$. Series compensation resonant capacitors ; C_1 , C_2 and roller load parameters (L_1 , k , τ) including two lossless inductor snubbers configure a load resonant tank circuitry. The switching frequency f_s is designed to be less than natural oscillation frequency f_d of the resonant tank. When the inverter switching frequency f_s becomes smaller than half of load resonant frequency f_d , the discontinuous current mode appears in which the load current becomes zero and active power switches can completely achieve ZCS. By inserting the lossless inductor snubbers, the zero current soft switching can be realized in the continuous mode.

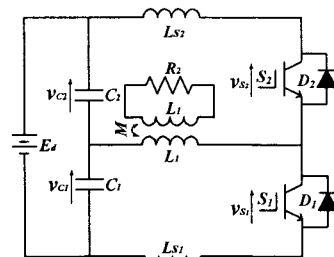


Fig. 5. ZCS-PFM high frequency inverter using IGBTs

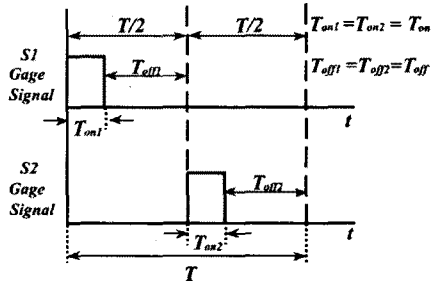


Fig. 6. Gate pulse voltage signal timing sequences

In this application specific inverter, both active power switches can respectively operate under stable ZCS commutation in spite of PFM scheme. The output power of this inverter is continuously regulated on the basis of the PFM scheme. The mode transition of this high frequency inverter circuit and its equivalent circuit are shown in Fig. 7.

The periodic steady state voltage and current waveforms of this inverter under the discontinuous current mode and continuous current mode are respectively illustrated in Fig. 8 and Fig. 9.

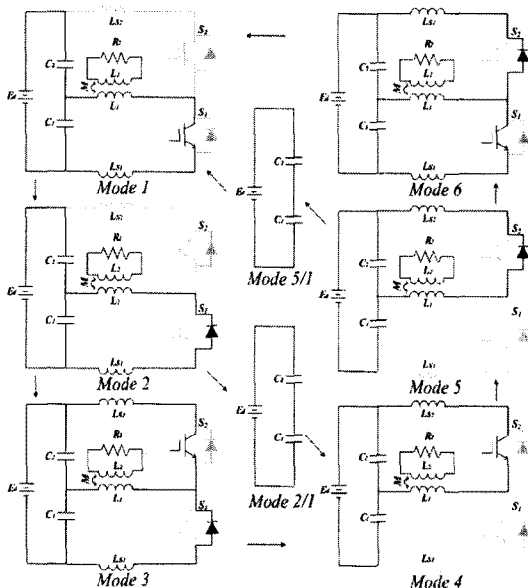


Fig. 7. Mode transitions and equivalent circuits

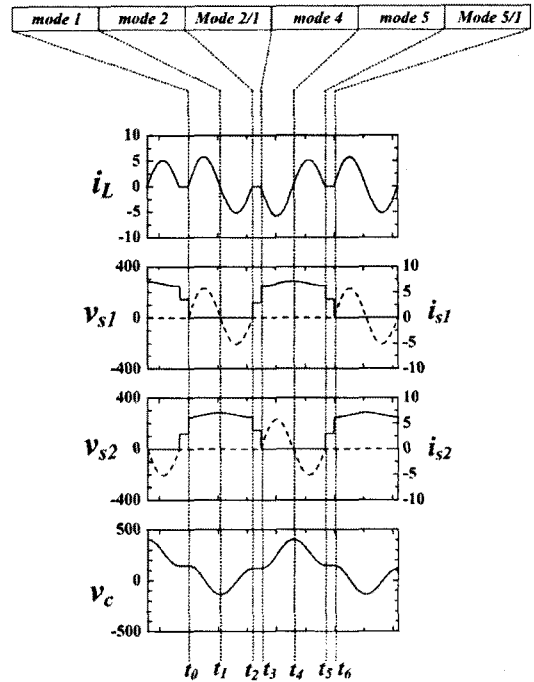


Fig. 8. Steady state operation waveforms in the discontinuous current mode

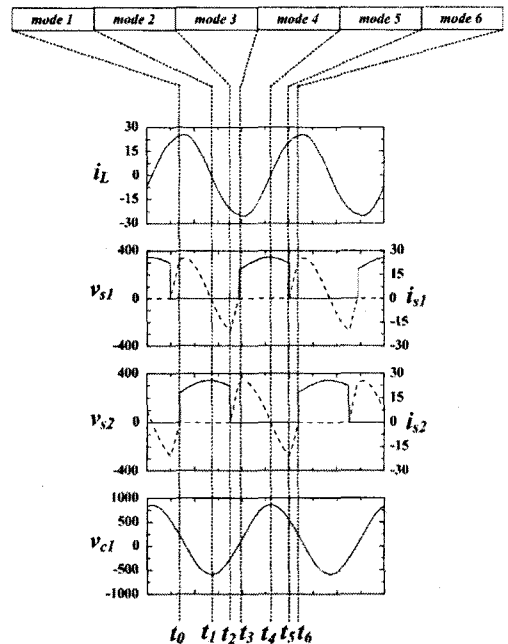


Fig. 9. Steady state operation waveforms in the continuous current mode

4. Experimental Results and Their Evaluations

The design specifications and circuit parameters of this inverter breadboard setup are indicated in Table 1. The soft-recovery high-speed diode (USR30P produced by Origin Electric Co. Ltd.) is used in parallel with reverse blocking IGBT (CT75AM-12 produced by Mitsubishi Electric Co. Ltd.) of the TO-3P package for this high frequency inverter circuit.

Table 1. Design specifications and circuit parameters

Parameter	Value	
DC voltage supply (E_d)	282.8[V]	
Resonance capacitor (C_1, C_2)	0.07[μ F]	
Lossless inductor (L_{s1}, L_{s2})	11.0[μ H]	
Inductance of working coil(L_1)	80.0[μ H]	
Induction heated roller load	τ	6.0[μ s]
	k	0.65
IGBT as active power switches	V_{CE}	600[V]
	I_C	75[A]
Reverse conducting diode	V_{RM}	600[V]
	I_0	50[A]

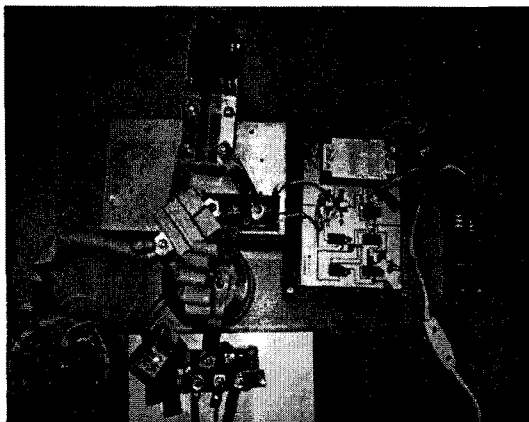
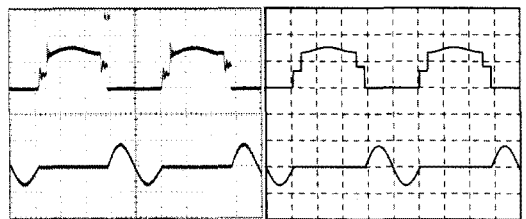
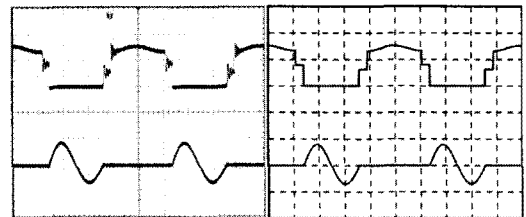


Fig. 10. Photograph of the trial manufacture

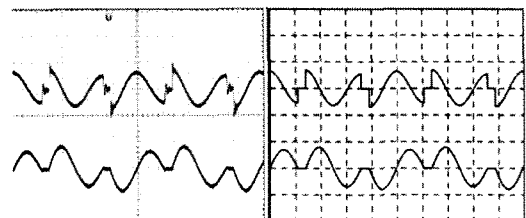
In the case of introducing active power switches; IGBTs in parallel with diode D_1 and D_2 , upper limitation of the switching operating frequency is designed as 45[kHz], and the lowest operating frequency is designed so as to operate outside the audible frequency region. Developed prototype of proposed lossless inductor snubber-assisted high frequency ZCS inverter with gate drive circuit are shown in Fig. 10.



(a) Voltage and current waveforms of the S_1



(b) Voltage and current waveforms of the S_2



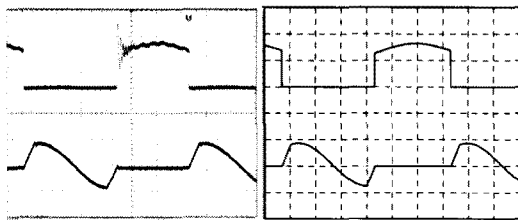
(c) Voltage and current waveforms of the working coil

Fig. 11. Steady state operation waveforms in the discontinuous current mode(200(V/div), 8(A/div), 10(usec/div))

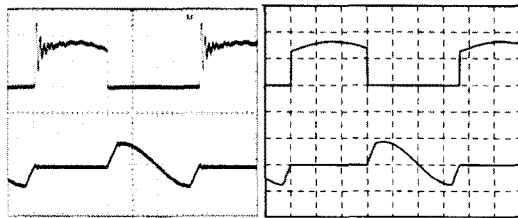
The experimental operating waveforms and the simulation waveforms are respectively illustrated in Fig. 11 and Fig. 12.

Fig. 11 and Fig. 12 display steady state operation

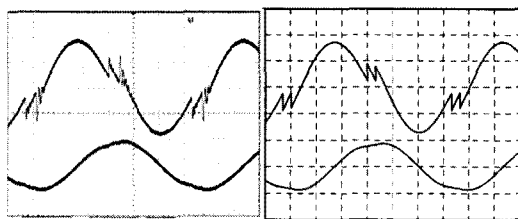
ration voltage and current waveforms in discontinuous current mode under switching frequency $f_s=20.5$ [kHz] as well as continuous current mode at an inverter switching frequency $f_s=37.5$ [kHz]. The voltage and current waveforms of the active power switching block ; Q_1 and Q_2 as well as the working coil depicts the upper traces. The operating waveforms in the left side are observed ones. The operating waveforms in the right side are comparative simulation ones. In addition, voltage and current waveforms are respectively illustrated in upper trace and under trace.



(a) Voltage and current waveforms of the S_1



(b) Voltage and current waveforms of the S_2



(c) Voltage and current waveforms of the working coil

Fig. 12. Steady state operation waveforms in the continuous current mode(200[V/div], 20[A/div], 4[usec/div])

Observing all experimental and simulation operating waveforms, the simulation and experimental results have good agreements, for high frequency load resonant inverter with the induction-heated roller load. It is proven that the power semiconductor switch can completely achieve the ZCS commutation operation even at the current continuous mode with the aid of two lossless inductor snubbers.

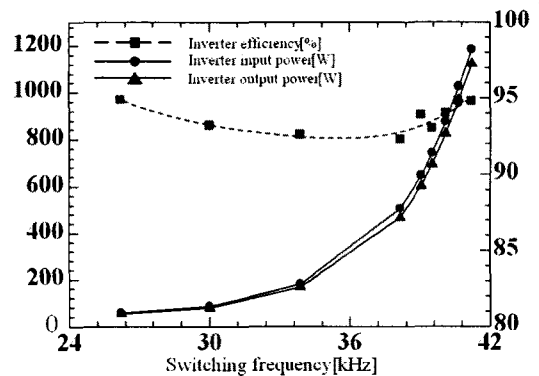


Fig. 13. Power regulation characteristics

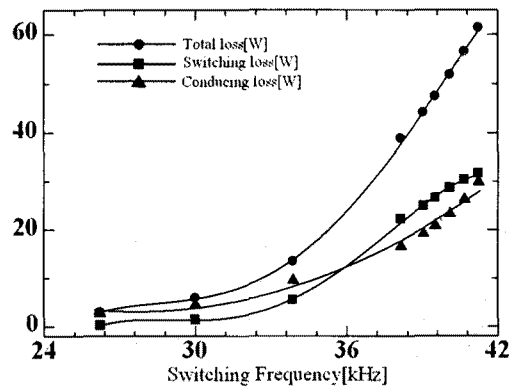


Fig. 14. Power loss analysis

Fig. 13 shows the power regulation characteristics of the high frequency ZCS-PFM inverter using IGBTs. The input electric power, the output power, power conversion efficiency of the inverter treated are illustrated graphically under a function of the switching operating frequency as a control

variable. It is proven that the output power of this inverter can be continuously adjusted by varying switching frequency of this inverter. Over the full output power range, the power conversion efficiency of this inverter is 92[%] in experiment.

In particular, the high efficiency over 94[%] can be also obtained in the copy mode and standby mode of copy machine using the induction heated fixing unit. It is verified the proposed high frequency load resonant inverter circuit operating under a principle of zero current soft switching is more effective for the future induction-heated rolling drum of the copy machine. In this circuit, switching loss by fall current and tail current in the turn-off does not occur, because the switch is being turned off, when the current is flowing in the reverse conducting diode of the switch. The power loss are mainly conduction loss of the switch (IGBT and diode for reverse conducting) and switching loss in the switch turn-on. Then, the switching loss of the inverter can be required using the total loss by test experiment and conducting loss. The power loss analysis result of this inverter is respectively shown in Fig. 14. In high power range (in the copying mode), the inverter power loss it tends to increase, while the switching frequency increases. The current stress di/dt in switching turn-on be alleviated employing loss less inductor and the switching loss can be reduced. On the other hand, in the lower power range(in the standing mode), the current discontinuous mode occurs, and the switching loss is very small, and it is proven that the conduction loss equals the inverter power loss almost.

4. Conclusion

A novel prototype of loss less inductor snubber-assisted ZCS PFM high frequency load resonant inverter using IGBTs for the induction heated

rolling drum for the fixing unit in copy machine was proposed originally, and the steady state operation principle of this inverter was clearly described from a practical point of view. In addition, the steady state operation and the power regulation characteristics of this inverter were quantitatively evaluated under varying switching frequency control implementation. It was proven from an experimental point of view that inverter output power could be continuously adjusted and complete soft switching commutation of this inverter was effectively possible even in the higher output power range with continuous load current mode by inserting lossless inductor snubber in series with each active power switch.

It was experimentally confirmed that this ZCS inverter topology is more effective and acceptable for toner fixing process in copy machine. In the future, the comparative studies between ZCS-PFM and ZVS-PWM load resonant inverter should be investigated for induction heated rolling drum of the copy machine in next generation.

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Biography

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