Online Control of AC/AC Converter Based SHEPWM Technique

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***Abstract*- Conventional online control of AC/AC converter controlled by the selective harmonic elimination pulse width modulation technique (SHEPWM) is based on storing the off-line calculated switching angle values in a form of lookup table. Then the required switching pattern of certain modulation index (M) is searched through the lookup table. This methodology suffers from limited system flexibility. This paper introduces a novel implementation scheme based on real-time calculation of the required SHEPWM switching pattern with linear control of the fundamental voltage component magnitude based on curve fitting technique for the exact switching angle trajectories. The accuracy of the derived polynomials is evaluated by calculating converter performance parameters using the approximated switching angles solutions obtained from the introduced method and the exact switching angles solutions. Detail of the introduced methodology is presented. Simulation and experimental results have been carried out to confirm the validity of the introduced algorithm.**

***Index Terms* — AC/AC Converter, Curve fitting technique, SHEPWM, THD,…**

I. INTRODUCTION

Power quality is an important issue for all power electronic apparatus. Among all of them AC/AC and DC/AC converters have wide industrial applications. This is due to their simple construction, ability of controlling large amounts of power in an economical base [1-2]. Online control for DC/AC converter is reported in recent literatures [3-4]. While online control for AC/AC converter has less interest in recent literatures.

Traditional control techniques for AC/AC converter such as line commutated phase-angle control and integral-cycle control are widely used. These control techniques have many drawbacks such as retardation of the switching angles causing lagging power factor, presence of lower order harmonics in the converter output voltage and discontinuity of power flow [5-8].

Modern control techniques such as PWM techniques are reported for controlling AC/AC converter in recent literatures [9-13]. This is to gain benefits such as linear control of converter output voltage with eliminating preselected lower order harmonics, possibility to optimize certain performance parameters, better transient response, improved input power factor. Among PWM techniques the Selective Harmonic Elimination Pulse Width Modulation technique is widely used in power electronics industrial applications, specially in AC/AC and DC/AC converters [14-18]. The SHEPWM technique has many advantages in comparison with the traditional PWM techniques (carrier based PWM techniques). These advantages are low switching losses, linear control of the fundamental voltage magnitude, elimination of preselected lower order harmonics from converter output voltage and the facility to leave the triplen harmonics uncontrolled to use the benefit of three-phase system circuit topology. The main disadvantage of the SHEPWM technique is the difficulty of calculating the required switching angles, which satisfy certain optimization criteria. This is because the system set of equations derived by using Fourier analysis are nonlinear and transcendental in nature, therefore multiple solutions are expected and convergence is highly dependent on the initial guessing values of the equations roots [19]. Real-time implementation of the SHEPWM technique in controlling AC/AC voltage controller output voltage magnitude and harmonic profile is not practiced to be implemented due to the aforementioned problems. It is reported in [20] that the lookup tables for the pre-calculated (off-line) SHEPWM switching angles values are to be programmed in a microprocessor's memory to allow online calculation of the required switching angles at certain modulation index using simple interpolation techniques for real-time operations in case of DC/AC converter. This approach is time consuming especially when dealing with large number of switching angles as well as it will increase the memory requirement. Another problem raised is that the approximation of the exact angle solutions by using this approach will affect the overall system flexibility and

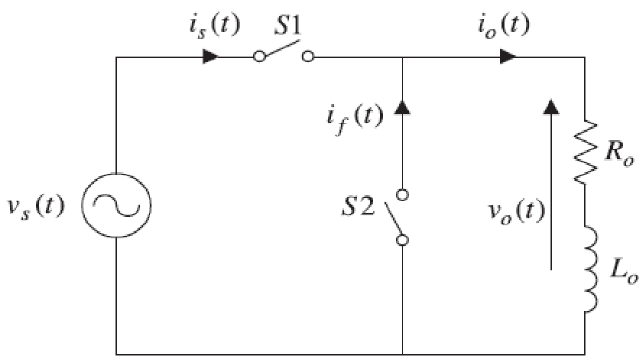

Fig. 01 - PWM AC/AC converter

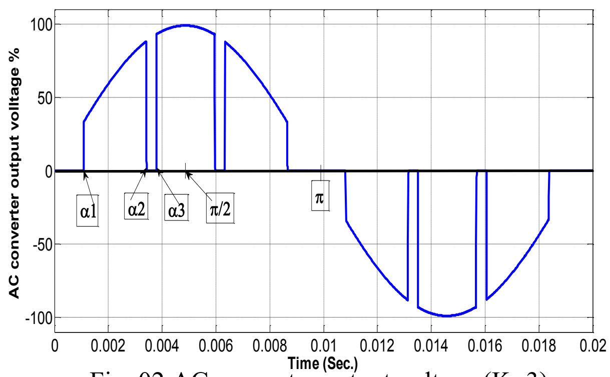

Fig. 02 AC converter output voltage (K=3)

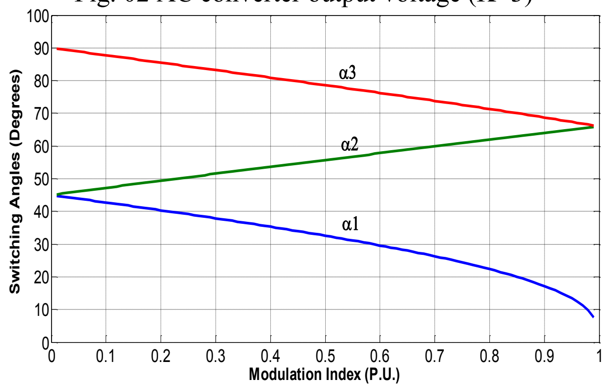

Fig. 03 Exact switching angles versus M (K=3)

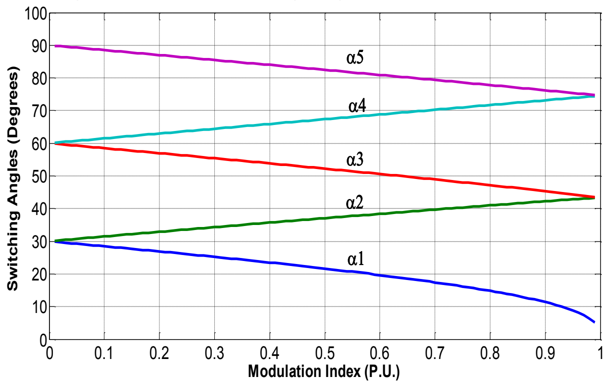

Fig. 04 Exact switching angles versus M (K=5)

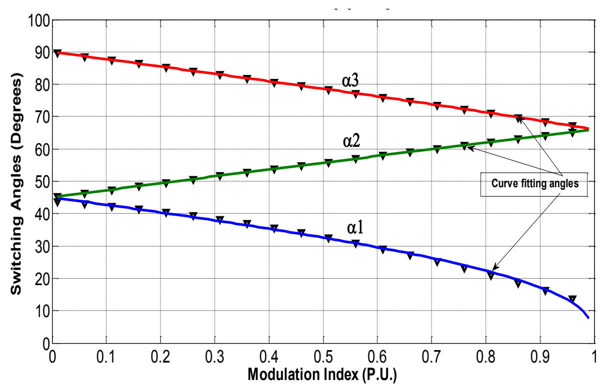

Fig. 05 Exact and fitted switching angles versus M (K=3)

accuracy [3].

The visual appearance of the exact solutions trajectories of the switching angles in the case of the SHEPWM technique controlling AC/AC voltage controller reported in [9,21] explicate that solutions trajectories can be replaced by curve fitting polynomials. This is will facilitate online control of AC/AC converter output voltage magnitude and harmonics profiles with improved control range and resolution. The curve fitting technique will replace solution of the nonlinear transcendental set of equations to just addition and multiplication processes with the facility of elimination preselected lower order harmonics depending on the SHEPWM technique characteristics.

In this paper curve fitting quadratic polynomial using least square method for the exact angles solutions trajectories were performed to permit online in real-time calculation of the SHEPWM switching patterns with linear control of the fundamental voltage component. The feasibility and the effectiveness of the proposed approach are evaluated through comparing quality factor such as the total harmonic distortion (THD), by calculating its value using the exact switching angles solutions and the switching angles solutions calculated from the curve fitting polynomials. In order to validate the introduced algorithm, simulation using Matlab/Simulink package and low power experimental prototype setup were conducted.

The paper is organized such as: Section II presents an overview of the SHEPWM technique as applied to AC/AC voltage converter. The curve fitting technique is given in section III. Theoretical, simulation and experimental results are given in Section IV. Conclusions are given finally in section V, followed by the list of references.

II. SHEPWM Technique for AC/AC Voltage Controller

The basic circuit of a simple PWM AC/AC converter consists of two switches arranged as shown in Fig. 01. Back-to-back switch (S1) provides power control to be delivered to the load, while switch (S2) provides a freewheeling path to discharge stored energy when (S1) is turned-off in case of stored energy loads. Switch S2 can be removed in case of resistive load only [6].

Reference to the SHEPWM technique characteristics, by setting K chops per quarter cycle, (K-1) preselected lower order harmonics can be eliminated from converter output voltage, the remaining degree of freedom is used to control the fundamental voltage component magnitude [14-15]. Maximum lower order harmonic to be eliminated is equal to (2K-1). For example, in single-phase system if K=5, the 3^{rd}, 5^{th}, 7^{th} & 9^{th} lower order harmonics can be eliminated from the converter output voltage. The dominant harmonic in this case will be the 11^{th} harmonic. In case of three-phase system if K=5, the 5^{th}, 7^{th}, 11^{th} & 13^{th} harmonics will be eliminated from converter output voltage. The dominant harmonic in this case will be the 17^{th} harmonic. Presented higher order harmonics in the converter output voltage can be easily eliminated by selecting suitable filter depending on the power

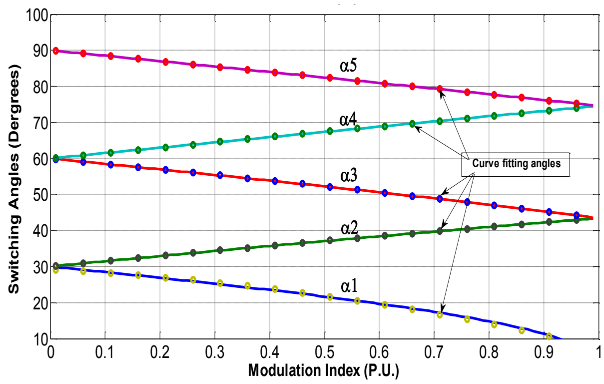

Fig. 06 Exact and fitted switching angles versus M (K=5)

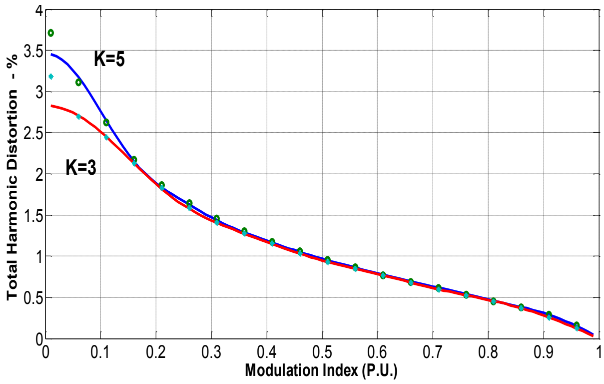

Fig. 07 THD versus modulation index
-solid lines are for exact angles solutions
-symbols are for fitted angles solutions

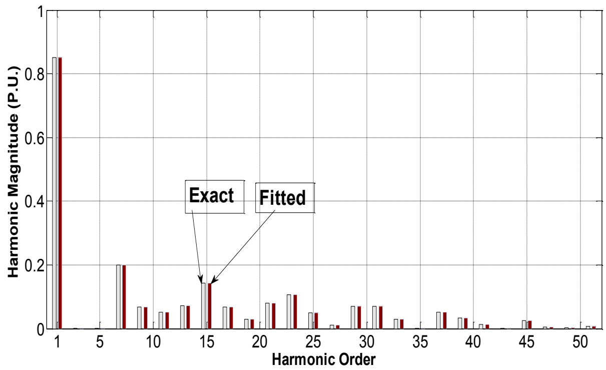

Fig. 08 Harmonic spectrum for exact and fitted switching angles versus harmonic order (K=3)

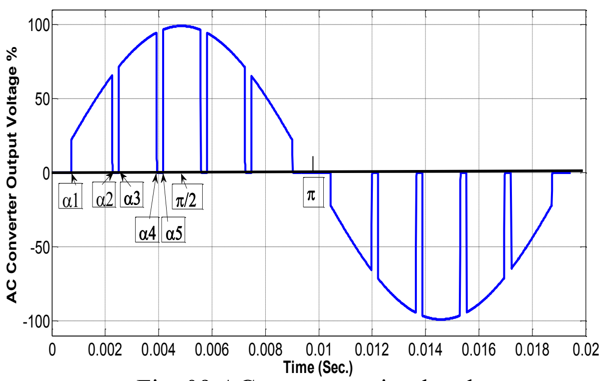

Fig. 09 AC converter simulated output voltage at K=5 & M=0.85 P.U.

quality measures.

The output voltage waveform from AC/AC converter in case of K=3 is illustrated in Fig.02. Switch S1 is turned-on at odd switching angles and turned-off at even switching angles. While the switch S2 is turned-on and turned-off in complement manner of switch S1.

Fourier analysis is used to derive the general AC/AC converter normalized output voltage formula as follows:

$$v_o(\omega t) = \sum_{n=1,2,3,\ldots}^{\infty} (A_n \cos n\omega t + B_n \sin n\omega t) \quad (1)$$

The output voltage general formula can be reduced due to half-wave and odd-wave symmetry characteristics of the output voltage waveform to [13]:

$$v_o(\omega t) = \sum_{n=1,\,3,\,5\ldots}^{\infty} B_n \sin n\omega t \quad (2)$$

Where B_n is the Fourier coefficient for the nth voltage component.

Equation (2) is normalized to the base supply maximum voltage (V_m) of 311 Volt.

Apply (2) in case of the SHEPWM technique with K chops per quarter cycle yields to the converter general output voltage components as [10]:

The fundamental voltage component:

$$B_1 = 1 + \frac{2}{\pi} \sum_{i=1,2,\ldots}^{K} (-1)^i \left(\alpha_i - \frac{\sin 2\alpha_i}{2}\right) \quad (3)$$

The harmonic voltage components:

$$B_n = \frac{2}{\pi} \sum_{i=1,2,\ldots}^{K} (-1)^i \left(\frac{\sin(n-1)\alpha_i}{n-1} - \frac{\sin(n+1)\alpha_i}{n+1}\right) \quad (4)$$

For n = 3, 5, 7,..., (2K-1) Under these constrains,

$$\alpha_1 < \alpha_2 < \ldots . < \alpha_K < \frac{\pi}{2} \quad (5)$$

The modulation index is defined in this case as $M = B_1/V_m$

The objective is to calculate the switching angles using the derived set of equations (3) & (4) under the constrains given in (5), which satisfy certain optimization criteria. Solutions of the derived set of equations depend on iteration methods or optimization techniques [9-12]-[22-26].

III. Curve Fitting Technique

The exact angles solution trajectories for AC/AC converter controlled by the SHEPWM technique in the case of K = 3 & 5 are shown in figures 03 & 04 [21]. The visual appearance of these angles solution trajectories suggested that curve fitting quadratic polynomial may be sufficient, this is also depend on the accepted level of accuracy. The curve fitting quadratic polynomials are obtained by using the built-in Matlab function "***polyfit***", in which it is found to be sufficient as a tool for the best approximation of the exact angle solution trajectories in this study.

In this case each angle solution trajectory is modeled by quadratic polynomial as in the followed form:

$$\alpha_i = a_{1i} + a_{2i} M + a_{3i} M^2 \qquad (6)$$

For i =1, 2, 3, …, K

Where; α is the chop angles per quarter cycle.

a_1, a_2 & a_3 are the quadratic polynomials constants.

The quadratic polynomial constants are calculated by using the Least Square fit technique, which minimize the sum of the squares of the deviations between the exact and the calculated switching angle solutions.

A measure of the reliability of the curve fitting technique applied is to observe actual converter performance parameters. In this study the THD and the harmonics spectrum at certain M are compared by calculating them using exact switching angles solutions and by using switching angles solutions calculated from the fitted quadratic polynomial [27-29].

IV. Results

A. Theoretical Results

A program was designed using MATLAB package with the help of the built-in curve fitting "***polyfit***" function to calculate the fitted quadratic polynomial constants. The input to the program is the exact angles solutions at M values at certain K [21]. The output of the program is the fitted quadratic polynomials constants, the harmonic spectrum and the THD for the whole range of the modulation index. Table I listed the quadratic polynomials constants for the case of K=3 & K=5 obtained from the designed program. The output results are visually illustrated in comparison style between the exact switching angles solutions and the switching angles solutions calculated from the fitted quadratic polynomials. Figures 05 & 06 show the switching angles solutions for the case of K=3 & 5. The THDs for the K=3 & 5 are shown in Fig. 07. The harmonic spectrums for K=3 at M=0.85 P.U. for exact and fitted switching angles cases are shown in Fig. 08.

The visual appearances of the graphs shown in figures 05 to 08 for the exact and the fitted switching angles solutions cases are confirmed that the fitted quadratic polynomials are sufficient for modeling the exact switching angles solutions trajectories. The only deviation to this outcome is at lower values of M in this range $0 < M < 0.1$ P.U. If the converter is used with M values higher than 0.1 P.U. there will be no problem. But if it is required the converter to work at M less than 0.1 P.U., in the case the exact switching angles solutions trajectories may be divided into two segments. First one is from $0 < M < 0.1$ P.U. and the second one is from 0.1 P.U. to 1.0 P.U. This lead to model each angle solution trajectory by two quadratic polynomials, but only one polynomial is to be applied depending on the value of M. This is to avoid increasing the order of the fitted polynomial for best fitting of the exact angle solution trajectory and to keep real-time calculation of the switching angles in practical acceptable limit.

TABLE I

Quadratic Polynomials Constants at K=3 & K=5

K=3	a_1	a_2	a_3
α_1	-20.63	-11.54	43.81
α_2	-0.95	21.88	45.05
α_3	-2.34	-21.41	89.90

K=5	a_1	a_2	a_3
α_1	-13.69	-7.87	29.23
α_2	-1.36	14.80	30.01
α_3	-2.07	-14.33	59.95
α_4	-0.27	14.84	60.01
α_5	-0.64	-14.71	89.97

B. Simulation Results

A Simulink model for AC/AC converter was designed and built using Matlab/Simulink package. The aim of this model is to validate the proposed curve fitting technique. The model consists of two back-to-back transistors, control circuit (switching patterns generator) AC voltage supply and resistive load. The required switching patterns in real-time at certain M and frequency are generated by using the built-in pulse generator block in the Simulink package for one complete cycle and then they are repeated for the complete simulation time. The Simulink model was tested intensively for different values of K odd values and modulation indices based on exact switching angles and switching angles calculated by using the fitted quadratic polynomials. Selected results are only presented.

Figure 09 shows the corresponding AC/AC voltage controller output voltage for the cases of K=5, M=0.85 P.U., 220 V, 50 Hz and load resistance of 100 Ω. The load current waveform at the previous parameters will be similar to the voltage waveform except its magnitude, this is for resistive load. It is evident from this figure that the switching angles calculated by using the curve fitting quadratic polynomials can be used to generate the required SHEPWM switching patterns required to control AC/AC converter output voltage.

C. Experimental Results

In order to verify the achieved theoretical and simulated results, a low power laboratory prototype single-phase AC/AC converter was designed and built as shown in Fig. 10. The block diagram for this laboratory prototype is shown in

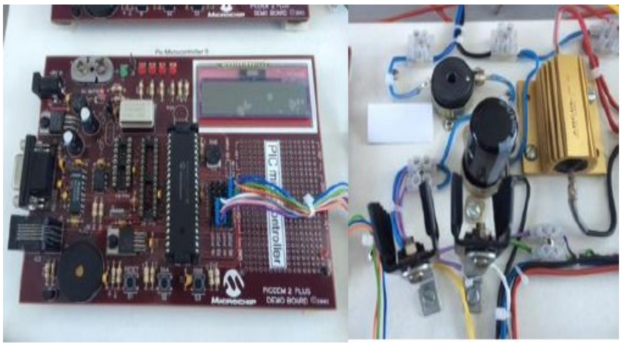

Fig. 10 – the experimental setup
(Microcontroller and MOSFET switches)

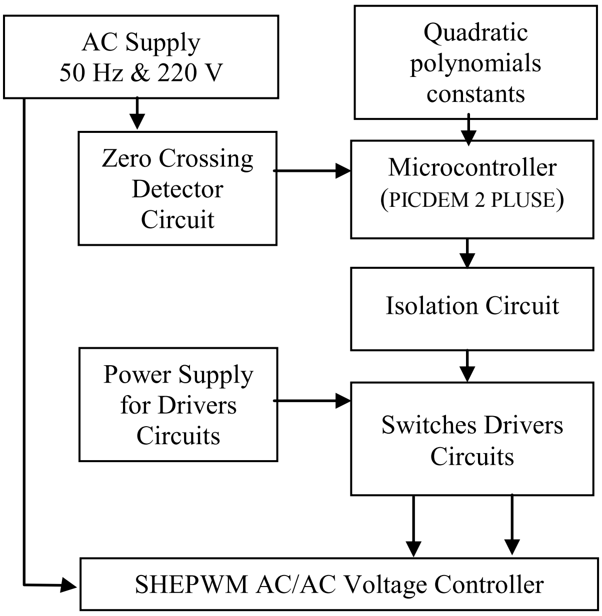

Fig. 11 Experimental prototype block diagram

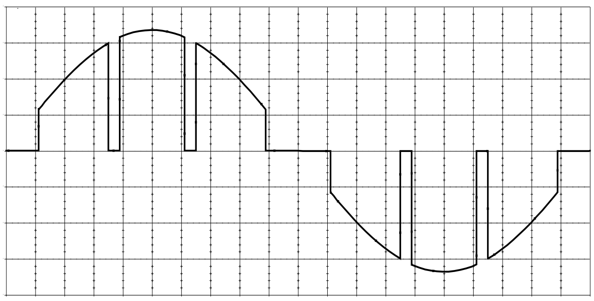

Fig. 12 – Experimental output voltage at
K=3 & M=0.85 P.U. (5 ms/div, 100 V/div)

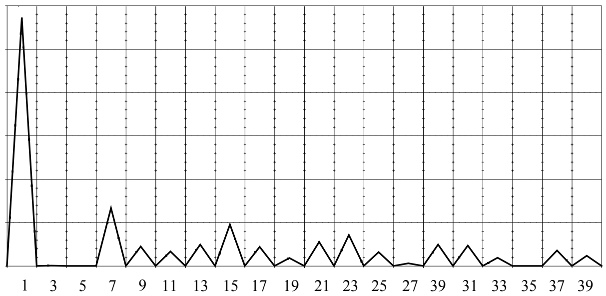

Fig. 13 – the voltage harmonic spectrum at
K=3 & M=0.85 P.U. (100 Hz/div, 50 V/div)

Fig. 11, which helps to track the flow of power and control signals. The experimental setup consists of three main circuits: power, control and isolation circuits. Power circuit consists of two bi-directional switches with internal anti-parallel diodes (MOSFET-IRF740). Control circuit uses PIC microcontroller (PICDEM 2 PLUSE DEMO BOARD) to generate the required switching patterns in real-time. A zero crossing detector circuit is used to synchronize the switching patterns with the supply voltage for proper converter operation. The isolation circuit is based on opto-coupler (HCPL2630). It is aim is to provide an electrical isolation between the control and the power circuits.

The quadratic polynomials constants for K=3 are stored in the microcontroller's memory. The microcontroller designed program uses these constants to calculate the switching patterns at certain input M value. The microcontroller generates the corresponding switching patterns for the converters' two switches in real-time synchronized with the supply voltage with the help of the zero crossing detector circuit.

The low power single-phase experimental prototype AC/AC converter is loaded with resistive load for simplicity and to focus on the converter control technique. The AC/AC experimental voltage controller output voltage for K=3 at M=0.85 P.U., 220 V, 50 Hz and 100 Ω resistive load is shown in Fig. 12. The harmonic spectrum for the same previous case of study is shown in Fig. 13. It is evident from this figure that the preselected lower order harmonics to be eliminated from the converter output voltage are eliminated. This proves the validity of the proposed curve fitting technique.

V. CONCLUSIONS

This paper presents a curve fitting technique to model the exact SHEPWM switching angles trajectories using quadratic polynomials used for controlling AC/AC converter output voltage fundamental magnitude and harmonic profiles. This is validated online calculation of the required switching angles with the help of the high speed calculation capabilities of low cost microcontroller. The simulation and the experimental achieved results validated the proposed algorithm.

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