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LOAD OPTIMIZATION METHODS FOR A MAXIMUM POWER POINT TRACKER USED IN SOLAR PANELS

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Abstract- Solar energy, and especially photovoltaic energy generation, is increasing its ratio all around the world. It is due to different factors, although the main three of them are the pollution and global warming, the energy independence, and the cost of the fossil fuels. In this increment of the photovoltaic generation, a main role is played by the energy policy of governments and the different weather conditions of the countries. In the process to generate energy from the solar resource, photovoltaic solar cells are the key element. In order to take advantage of the maximum of the energy that could be possible to use to this generation, some techniques, such as solar trackers, are incrementing their use. In this sense, power delivery by solar cells is a function of the voltage at their terminals and has a maximum point. Several control algorithms have been developed during the last decades to optimize the control operation. In this paper, an analysis of maximum power point tracking algorithms for DC-DC converters in photovoltaics arrays is done.

Keywords: Photovoltaic Energy Generation, Solar Cell, Maximum Power Point, Tracking.

I. INTRODUCTION

Energy transition from fossil fuels to renewable sources, like solar energy in any of its cases (photovoltaic, thermal, etc.), is coming at different speeds depending on the country or region. In general, the problem of pollution and global warming have gained space for discussion in public opinion, and many countries, especially Spain, where initiatives have been taken to implement alternative energy systems by replacing the use of hydrocarbons to generate electric energy [1, 2].

Different studies and analysis about the cost and the real energy supply, if fossil fuels are practically eliminated, say that this transition is possible and, in the main of the cases, it depends on the political decision in order to face it with guarantees [3, 4, 5]. Not only in Europe, but in all around the world, photovoltaic power generation is increasing ratio of the electricity market. Several factors can be taken into account to explain this circumstance: photovoltaic power generation needs normally low maintenance, its components suffer in a low level because there is a minimum of moving parts (and sometimes they do not exist), there is not audible noise in contrast with wind power generation, there is not a fuel cost, and it is ecological generation because after installation, operation does not pollute [6, 7].

As we can see in the Figure 1 for two different countries (Spain and Azerbaijan), the solar energy is highly conditioned by the geographical area. In a same country, distances of some kilometers are important to obtain different amount of radiation received.

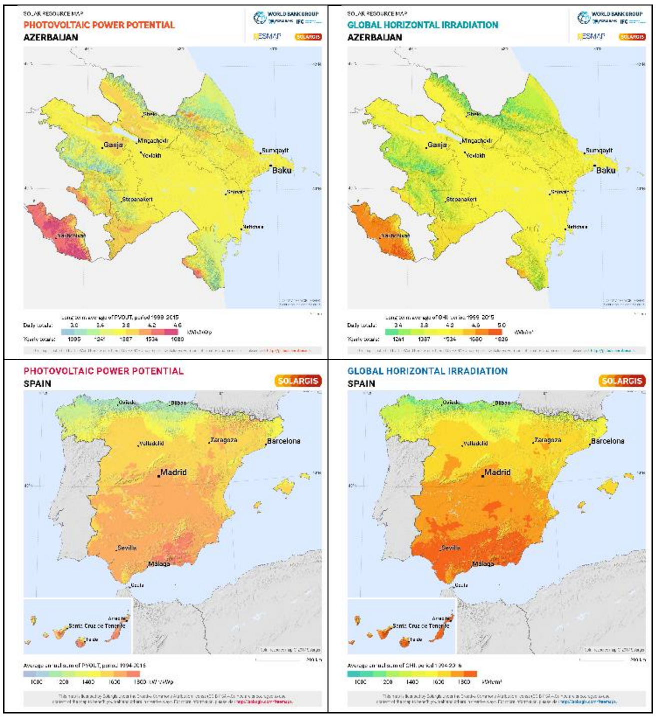

Figure 1. Photovoltaic power potential and global horizontal irradiation for Azerbaijan and Spain. Solar resource map © 2018 Solargis. Licensed under the Creative Commons Attribution license (CC BY-SA 4.0). https://solargis.com

It also depends on the time of day and the weather conditions, in addition that the consumption of it is independent of the amount of radiation received and depends exclusively on the needs of the user, so it is necessary to store this energy to then make the most of it.

It is important, therefore, to have a bank of batteries in a photoelectric installation and even more important is the charging method of the battery bank.

The proper charge of a battery improves its operation and also prolongs the life of it, saving money. On the other hand, the energy used to charge a battery must be used to maximum, since components that convert solar energy into electricity are expensive, so a good use of this energy contributes to the reduction of operating costs.

Among different technologies for solar energy generation, implementation of photovoltaic (PV) systems has taken a particular success related to the geographical installation, growth percentage of installation, electricity generation, and reduction of manufactured costs. The main reason has been the government's policy with the feed-in tariffs. Other reasons have been that on the one hand PV is extremely modular, so easy and fast to install (both for individual systems and for energy farms) and accessible to the general public [8]. Even roof-top PV in sunny countries can compete with high retail electricity prices [9]. Distributed generation and microgrids are also increasingly common in power systems [10].

II. SOLAR CELLS AND DC-DC CONVERTERS

The transformation of solar energy to electrical energy is possible through the photovoltaic effect using solar cells. The base material of most solar cells is silicon.

As the structure that makes up the solar cell is constituted in the same way as a diode, (which is also a p-n junction), the current that flows through it can be expressed as the diode current, which is shown in the Equation (1).

$$I_D = I_0 \cdot \left[\exp\left(qV / kT \right) - 1 \right] \tag{1}$$

where, I_D is the diode current [A], q is the charge of the electron (1.6×10^{-19} J), V is the voltage applied between the terminals [V], k is the Boltzmann's constant (8.65×10^{-5} eV/ºK), T is the temperature in Kelvin degrees [ºK], and I_0 is the saturation current of the diode [A].

The process of absorbing the energy of solar radiation is called photoelectric absorption. According to Kininger [11], during the interaction of sunlight and a silicon solar cell, about 60% of the energy is lost, it is not converted into electrical energy, because the energy of the photons is much greater or much less than the prohibited band.

Figure 2 shows the schematic of the equivalent model of an ideal solar cell. The diagram consists of a p-n junction diode and a current source representing the photocurrent, whose magnitude depends on the intensity of solar radiation.

The mathematical model represented by this diagram is shown in Equation (2).

$$I_{cell} = I_{ph} - I_D = I_{ph} - I_0 \cdot \left[\exp\left(qV / kT \right) - 1 \right] \tag{2}$$

When the terminals of the solar cell are short-circuited (R_{load} = 0) we find that V_D = 0, so that the current of the cell is equal to the photocurrent, as shown in Equation (3), and this current is called short circuit current I_{sc}.

$$I_{sc} = I_{cell} = I_{ph} \tag{3}$$

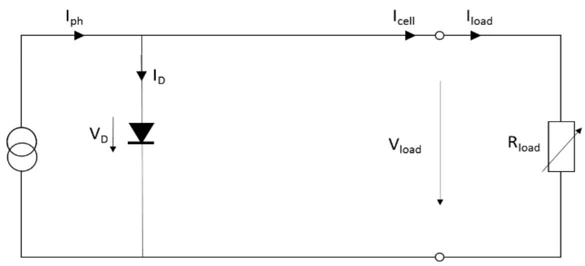

Figure 2. Circuit diagram equivalent of an ideal solar cell connected to a load

On the other hand, when placing the terminals of the solar cell in open circuit ($R_{load} = \infty$) we find that the voltage that falls in the terminals is represented in the Equation (4), which is called open circuit voltage V_{oc}.

$$V_{oc} = \frac{kT}{q} \cdot L\left(\frac{I_{ph}}{I_0} + 1 \right) \tag{4}$$

With these two equations, the *I-V* ratio of a solar panel can be generated.

It can be observed in Figure 3 that for different panels with lower values of short circuit currents I_{sc}, their characteristic *I-V* tend to shrink, and to enlarge if this value is greater. It must be remembered that since I_{sc} depends proportionally on the received solar radiation, it also affects proportionally in the height of the graph. Analogously it occurs with V_{oc}, since at lower values the graph tends to narrow and vice versa. This also occurs when different configurations of solar panel configurations are carried out in series (increases V_{oc}) or in parallel (increases I_{sc}).

Figure 3 also shows the graph of power versus voltage, which gives us an idea of which and where maximum power is located. This point is very important since we want to get the most out of the solar panel. It should be remembered that this graph is generated based on the ideal model described above.

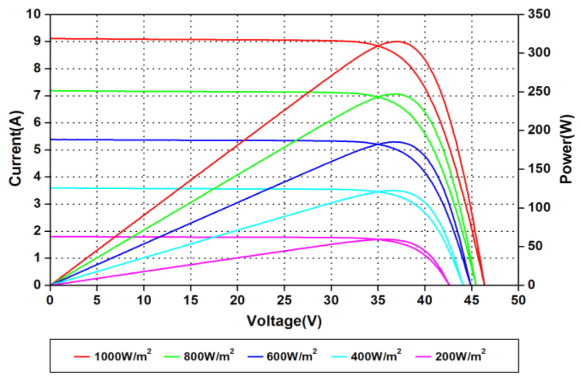

Figure 3. Current-Voltage and Power-Voltage curves at different irradiances. Taken from the AS-6P polycrystalline module of Amerisolar

The output power of the photovoltaic systems can vary dramatically in seconds. With high levels of penetration of PV, this intermittent can cause problems with the supply operations and in the equipment due to these voltage fluctuations. This requires equipment for regulating the output voltage of these facilities. These will be the DC/DC converters.

All the photovoltaic installation engaged in the production of electricity will use this component, either stand-alone (Buck) or connected to the grid (Boost) [10].

It can be seen then that the power delivered by the solar cells as a function of the voltage at their terminals has a maximum and from there it decays. In order to optimize the control operation that allows to reach and maintain at this point, which is called Maximum Power Point (MPP), there are many control algorithms.

III. OPERATION OF A LOAD OPTIMIZER FOR SOLAR CELLS. "MAXIMUM POWER POINT TRACKER" (MPPT)

The function of an MPPT is to extract the maximum power from the solar panels, which is formed by a DC-DC converter that is usually connected between the solar panels and the load.

The panel current depends on the incident radiation intensity of the sun, so the power delivered by it depends on the environmental factors where the solar panel is located. The cloudiness of the environment, the density of the air, the inclination of the incidence of the sun to the surface of the panel, the environmental and panel temperature, the rain, like many other environmental factors, are difficult to predict and are impossible to control. These are some reasons because the transfer function of a solar panel varies with time in an unknown way.

The control algorithm of the MPPT must be continuously adjusting the point of operation to try to stay in the MPP, since this depends on many environmental factors and these are changing as explained above. Therefore, the algorithm has to discern if the point where it is at that moment delivers more or less power than in the previous instant, since it can be seen in Figure 3 that there is only a unique maximum.

What usually happens, it is that the controller applies a variable load on the panel until it finds the maximum power it can deliver, and it maintains it while the conditions do not change. Then, if a disturbance occurs in the environment, the incidence of the sun with a different angle to the panel is applied, then the algorithm must change the load again without interrupting the flow of power delivered, until the new MPP is found again, and so on, while the sun is present.

IV. LOAD OPTIMIZATION METHODS FOR AN MPPT

At present, we can find many different methods for the control of an MPPT. Each one of these techniques pretends to find autonomously the V_{mpp} voltage and the I_{mpp} current of the solar panel in order to obtain the maximum P_{mpp} output power at a given radiation and temperature.

A. Methods of Perturb and Observe (P&O) and Hill-Climbing

Both methods, P&O and Hill-climb, are very similar, since they make a disturbance in the system. The P&O method disturbs the operating voltage of the solar panel, while "Hill-climbing" disturbs the duty cycle of the DC-DC converter. By disturbing the duty cycle, both the operating voltage and the operating current are perturbed.

It can be observed in Figure 3 that, when increasing the operating voltage below the V_{mpp}, the power increases, so the next disturbance must be the same as the previous one. But if, when increasing the voltage, a decrease in power occurs, then it is above the V_{mpp}, so the next disturbance must be the inverse of the previous one.

These methods, although simple to implement and without much complexity, present certain disadvantages with respect to others. They use a fixed disturbance over time and this generates the following: if the disturbance is large, the convergence time is smaller but the oscillation around the MPP becomes large; and on the other hand, having a small disturbance, the oscillations are reduced but the time of convergence increases. Therefore, in order to improve both characteristics, not only a fixed size of disturbance can be implemented but a different set of disturbances. Unfortunately, this would make the algorithm more complex.

Figure 3 also shows the power characteristic vs. voltage for different atmospheric conditions. Suppose a group of clouds cover the solar panels, and after a while the sky clears, which represents more radiation in the panels (and, therefore, more power). If the controller was in the MPP, at the beginning, when there were clouds, and the change in atmospheric conditions occurs between a sampling period, the operation point jumps from this point to another higher in the graphic. So, this will represent an increase in the power, and this control in the next sampling period keeps the step, and this generates a move away from the MPP. To avoid moving away so much from the MPP, one option is to compare the current operation point with two previous ones in order to determine a better decision in the next disturbance.

These methods require the measurement of power. Therefore, they need voltage and current sensors. Although depending on the DC-DC converter to be used, the value of the current can be approximated only by measuring the voltage. It is simple to implement and can even be done using analog circuitry instead of using a microcontroller.

B. Incremental Conductance Technique (IC)

By this method, the input impedance of the controller is adjusted to a value, which is equal to the optimum impedance of the panel, to certain atmospheric conditions. This method is based on the fact that the derivative of the power in the MPP is zero, positive to the left and negative to the right, as shown in Equation (5). In Equation (6), the derivative of the power is developed as a function of voltage and current.

$$\begin{cases} \dfrac{dP}{dV} = 0 & \text{at MPP} \\ \dfrac{dP}{dV} > 0 & \text{left of MPP} \\ \dfrac{dP}{dV} < 0 & \text{right of MPP} \end{cases} \quad (5)$$

$$\frac{dP}{dV}=\frac{d(I\cdot V)}{dV}=I+V\cdot\frac{dI}{dV}\cdot I+V\cdot\frac{\Delta I}{\Delta V} \quad (6)$$

Therefore, Equation (5) can be written as shown in Equation (7).

$$\begin{cases}\frac{\Delta I}{\Delta V}=-\frac{I}{V} & \text{at MPP}\\ \frac{\Delta I}{\Delta V}>-\frac{I}{V} & \text{left of MPP}\\ \frac{\Delta I}{\Delta V}<-\frac{I}{V} & \text{right of MPP}\end{cases} \quad (7)$$

The MPP can be found by comparing the instantaneous conductance (I/V) with the incremental conductance ($\Delta V/\Delta I$), as shown in the control algorithm in Figure 4. V_{ref} is defined as the reference voltage at which the solar panel is forced to operate.

When $V_{ref} = V_{mpp}$, the maximum power point has been reached and remains at this point of operation until ΔI changes. The algorithm increases or decreases the reference voltage until the MPP is found.

This method has the same problem that Perturb and Observe or Hill-climbing, since the step size is not variable. In addition, this method measures voltages and currents so it needs its respective sensors and saves the values at an earlier moment of them. Therefore, it requires the implementation of a microcontroller. In addition, it is a little more complex than the previous ones.

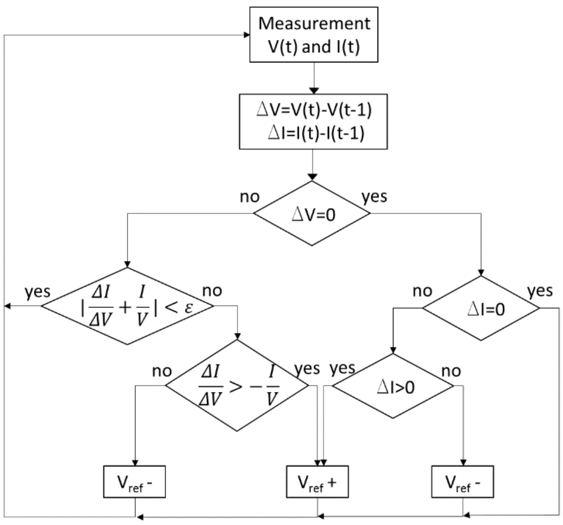

Figure 4. Algorithm of control of the IC method. Taken from the work done by Esram and Chapmam (2005)

C. Fractional Open-Circuit Voltage Method

This method is based on the close linearity between the voltage V_{mpp} and the open circuit voltage V_{oc}, under certain temperature and atmospheric conditions. The voltage V_{mpp} is approximated as directly proportional to the open circuit voltage, as shown in Equation (8).

$$V_{mpp}=k_1\cdot V_{oc} \quad (8)$$

The k_1 factor has been calculated empirically for different solar panels at different radiation and temperature conditions, and, in general, its value is between 0.71 and 0.78, so this method every certain time interval performs the measurement of the open circuit voltage V_{oc} and adjust the reference voltage $V_{ref}(t) = k_1\cdot V_{oc}(t)$. This method must disconnect the solar panel from the load to perform this measurement, which interrupts the flow of power. If this happens many times in a short time, power is lost, and if it happens a few times, you do not have the correct MPP value in the face of changing atmospheric conditions. One way to eliminate the constant disconnection between the panel and the load is using reference cells and these are measured V_{oc}, knowing that these cells and those used to feed the load are very similar.

This method does not find the real MPP, since it is an approximation. It can be close to the V_{mpp} in a very short time and it is very simple to implement. Other advantages are that it does not require a microcontroller and only uses a voltage sensor, but it is not a real MPPT.

D. Fractional Short-Circuit Current Method

This method is based on the fact that the maximum power current I_{mpp} is approximately proportional to the short circuit current I_{sc}, as shown in Equation (9).

$$I_{mpp}=k_2\cdot I_{sc} \quad (9)$$

This value of k_2 is around 0.78 and 0.92. This, like the previous method, must disconnect the load from the panels and short-circuit them in order to perform the current measurement. This method has the same strengths and weaknesses as the previous method, and it is not a real MPPT.

Both methods that have been explained above can be implemented in an easy way. In general, a real MPPT will vary the input impedance or the work cycle, but these, if they start to operate away from the MPP, would take a long time to reach. Therefore, it would be desirable to have a starting point, and this is where the methods of open-circuit voltage and short-circuit current are implemented.

E. Fuzzy Logic Control

The use of Fuzzy Logic for MPPTs has become more popular in the last time. Fuzzy control has also been extended to numerous applications including appliances and robots.

The control of Fuzzy Logic is advantageous when working with imprecise entries, to which a mathematical model cannot be defined. This control is normally made up of three stages: the first called fuzzification, which transforms the numerical variables into linguistic variables based on membership functions as shown in Figure 5. The second stage called the rule base in which a series of operations are carried out among the input linguistic variables. And finally, the defuzzification stage, which passes from the linguistic meaning to the specific numerical value of exit through its membership function.

Figure 5 shows that the five fuzzy levels that we have followed, according to Won et al. [12]: NB (Negative Big), NS (Negative Small), ZO (Zero), PS (Positive Small), PS (Positive Big). Depending on the desired precision, more or less membership functions are used.

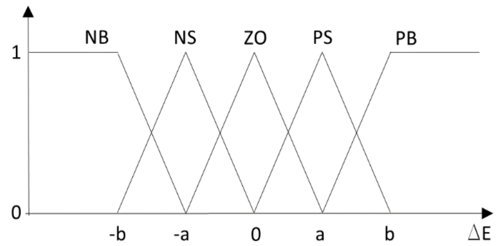

Figure 5. Membership functions for the input and output variables of a Fuzzy Logic control

The axis for abscises represents the numerical value of an input variable and the axis for ordinates represents the degree of belonging to which that input variable belongs to each function NB, NS, ZO, PS, PB. In some cases, these membership functions are constructed less symmetrically to give greater weight to specific fuzzy levels.

The inputs of a Fuzzy Logic controller for a commonly used MPPT are the error E and the error variation ΔE. The error E is defined as the variation of the power according to the voltage dP/dV, which represents the slope of the power vs. voltage, as it can be approximated in Equation (10). Therefore, ΔE is defined as the variation of the slope, as shown in Equation (11).

$$E(n) = \frac{P(n) - P(n-1)}{V(n) - V(n-1)} \tag{10}$$

$$\Delta E = E(n) - E(n-1) \tag{11}$$

Once the values of E and ΔE have been obtained, they are converted into linguistic variables by introducing them into membership functions. Then, we proceed to calculate the output of the controller, which is a variation in the work cycle called ΔD (change of duty ratio) through the rule base.

If the operation point is far from the MPP on the left, this means that E belongs to PB, and if ΔE belongs to ZO, then the variation of the duty cycle must be large and positive, ΔD belongs to PB. Looking at Figure 3 (*P-V* curve), we can see that if the operating point is to the left and far, it is equivalent to a voltage much lower than the V_{mpp}, so we have to increase the voltage, and it increases with increasing work cycle.

The Fuzzy Logic control for the MPPT, when using different degrees of belonging, is capable of having a variable output range. This improves the convergence time (since steps away from the MPP are large) and the oscillations around the MPP (since the steps are very small).

The implementation of this controller is more complex than previous methods, since it is necessary a good knowledge of the phenomenon to define the number of membership functions, the base of rules, the defuzzification method, etc.

In addition, it requires a voltage sensor and a current sensor to calculate the input power, at the same time it requires a microcontroller to store the previous values and carry out the linguistic operations.

V. CONCLUSIONS

Solar cells are the fundamental of a photovoltaic system for a power generation. Because most of the captured energy is transformed into heat and not electricity, it is very important to use techniques that can increase the efficiency of solar panels.

Working around the Maximum Power Point is one of the methods that help cell generate more power. There are several algorithms that try to make the solar cells work near that point. In this paper we have analyzed some of them, comparing not only the reach of the MPP but also its complexity and the needs, or not, of diverse measurement sensors.

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REFERENCES

[1] I.S. Nashawi, A. Malallah, M. Al-Bisharah, "Forecasting World Crude Oil Production Using Multicyclic Hubbert Model", Energy Fuels, Vol. 24, pp. 1788-1800, 2010.
[2] M. Asif, T. Muneer, "Energy Supply, its Demand and Security Issues for Developed and Emerging Economies", Renewable and Sustainable Energy Reviews, Vol. 11, Issue 7, pp. 1388-1413, Sept. 2007.
[3] N. Abas, A. Kalair, N. Khan, "Review of Fossil Fuels and Future Energy Technologies", Futures, Vol. 69, pp. 31-49, March 2015.
[4] J.J. Vidal Amaro, C. Sheinbaum Pardo, "A Transition Strategy from Fossil Fuels to Renewable Energy Sources in the Mexican Electricity System", Journal of Sustainable Development of Energy, Water and Environment Systems, Vol. 6, Issue 1, pp 47-66, 2018.
[5] J. MacNaughton, "Energy Security and the Role of Fossil Fuels Revisited", IEEJ Energy Journal, Special Issue, pp. 71-74, October 2017.
[6] B. Subudhi, R. Pradhan, "A Comparative Study on Maximum Power Point Tracking Techniques for Photovoltaic Power Systems", IEEE Transactions on Sustainable Energy, Vol. 4, pp. 89-98. 2013.
[7] A. Gurung, "Green Investing 2011: Reducing the Cost of Financing", World Economic Forum USA Inc., USA, 2011.
[8] J. Bilbao, E. Bravo, O. Garcia, C. Varela, M. Rodriguez, P. Gonzalez, "Looking Back: The Next Future of Solar Energy Generation", 8th International Conference on Technical and Physical Problems of Power Engineering (ICTPE-2012), No. 4, Code 00PLL04, pp. 13-17, Fredrikstad, Norway, 5-7 September 2012.
[9] M. Kaltschmitt, W. Streicher, A. Wiese, "Renewable Energy: Technological Foundations, Economical & Environmental Aspects", Springer, May 2007.
[10] J. Ramos Hernanz, J. Campayo, F. Oterino Echavarri, E. Zulueta, O. Barambones, U. Fernandez, J. Sancho, I. Zamora, "Main Converters DC/DC Used in Photovoltaic Systems", 8th International Conference on

Technical and Physical Problems of Power Engineering (ICTPE-2012), No. 87, Code 08RNE06, pp. 415-419, Fredrikstad, Norway, 5-7 September 2012.
[11] F. Kininger, "Photovoltaic Systems Technology", Institute for Rational Energy Conversion, University of Kassel, Kassel, Germany, 2003.
[12] C.Y. Won, D.H. Kim, S.C. Kim, W.S. Kim, H.S. Kim, "A New Maximum Power Point Tracker of Photovoltaic Arrays Using Fuzzy Controller", Power Electronics Specialists Conference, PESC'94 Record., 25th Annual IEEE, Taipei, Taiwan, 20-25 June 1994.

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