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LETTER TO THE EDITOR

NEW TRANSMISSION LINE SYSTEMS FOR ACCUMULATING POWER FROM DISTRIBUTED RENEWABLE ENERGY

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1. INTRODUCTION

Generation of electrical energy faces many problems today. In a world of growing environmental awareness, nuclear power plants find less and less acceptance and conventional combustion power plants are criticized owing to air pollution. The natural world is filled with a large amount of clean and safe renewable energy such as solar light, ocean waves, wind flow, etc. and therefore regenerative energy systems are becoming more important then ever. The common features of these energy sources are that the amount of energy in a locally small area is small and usually not stable and is therefore useless, while the amount of renewable energy over large areas is very large and is useful if it is collected effectively and stored safely.

Many converters such as solar modules, wave converters, wind turbines, etc. have been successfully developed to transfer renewable energy into electricity so far.[1–5] If all renewable energy were converted into DC electric sources by highly efficient DC-to-DC or AC-to-DC converters with maximum power point tracking (MPPT),[6–7] high-power regenerative systems could be created by directly connecting these DC current sources in parallel or directly connecting DC-to-DC voltage sources in series via DC mains. However, the electric stress applied to every converter along the DC mains will be increased as the total number of converters is increased, which implies that more costs will be incurred.

Innovative transmission line collection systems with lower costs and high efficiency are proposed in this paper. We assume that the renewable energy can be converted into AC electricity by DC-to-DC or AC-to-AC inverters with MPPT first. These collection systems are constructed from a large number of inverters which are dispersed over very large areas and connected by a transmission line network. The power from the renewable sources is automatically accumulated into a large power flow at the target load via the transmission line collection networks by using transmission line theory and the phase relation between sinusoidal outputs of inverters. Based on mathematical analysis, the electric stress of only those inverters which are closer to the target load is larger. Therefore the total costs of the proposed collection systems can be reduced effectively.

2. TRANSMISSION-LINE-TYPE VOLTAGE SOURCE AND CURRENT SOURCE

2.1. TL-type voltage source

A uniform transmission line of length l with characteristic impedance Z_O can be described by the two-port equations

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} A(l) & B(l) \\ C(l) & D(l) \end{bmatrix} \begin{bmatrix} V_2 \\ V_1 \end{bmatrix} \tag{1}$$

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where $A(l) = D(l) = \cos(2\pi l/\lambda)$, $B(l) = jZ_O \sin(2\pi l/\lambda)$ and $C(l) = jY_O \sin(2\pi l/\lambda)$ are functions of the length l. Figure 1(a) shows the schematic diagram of a transmission-line-type voltage source (TLT-VS) with n current sources, which are equally spaced along a transmission line of length $\lambda/4$ with characteristic impedance Z_O each, and a load resistance $R_L = Z_O$. The notation $I_{S,k+1}$ represents the phasor current of the $(k+1)$th current generator, where $k = 0. \ldots, n-1$. The length of transmission line between the current generator$_{S,k+1}$ and the open-circuited terminal is $k\lambda/4n$ and that between $I_{S,k+1}$ and the load R_L is $(n-k)\lambda/4n$. First, the equivalent circuit in Figure 1(b) can facilitate the output response at the load to the individual current source $I_{S,k+1}$. The phasor voltage drop V_{n+1} and the phasor current flow $I_{r,n+1}$ are obtained from

$$V_{n+1} = Z_O I_{r,n+1} = Z_O \cos\left(\frac{k\pi}{2n}\right) e^{-j\pi/2} I_{S,k+1} \tag{2}$$

The TLT-VS In Figure 1(a) can be regarded as a linear system. $I_{r,n+1}$ *and* V_{n+1} are really the sum of the response to individual current sources. Letting $I_{S,1} = I_{S,2} = \cdots = I_{S,n} = I_S$, the phasor voltage V_{n+1} across R_L is

$$V_{n+1} = Z_O \sum_{m=0}^{n-1} \cos(m\phi) e^{-j\pi/2} I_S = -j\frac{Z_O}{2}\left[\cot\left(\frac{\pi}{4n}\right) + 1\right] I_S \tag{3}$$

where $\phi = \pi/2n$. Notice that since the input impedance looking towards the transmission line of length $\lambda/4$ with an open-circuited terminal is equal to zero, the equivalent circuit of the TLT-VS at port $n+1$ is an ideal voltage source whose phasor voltage is V_{n+1}. Additionally, the desired equivalent voltage phasor V_{n+1}, created by properly selecting the current phasor I_S, is proportional to the total number n of sources.

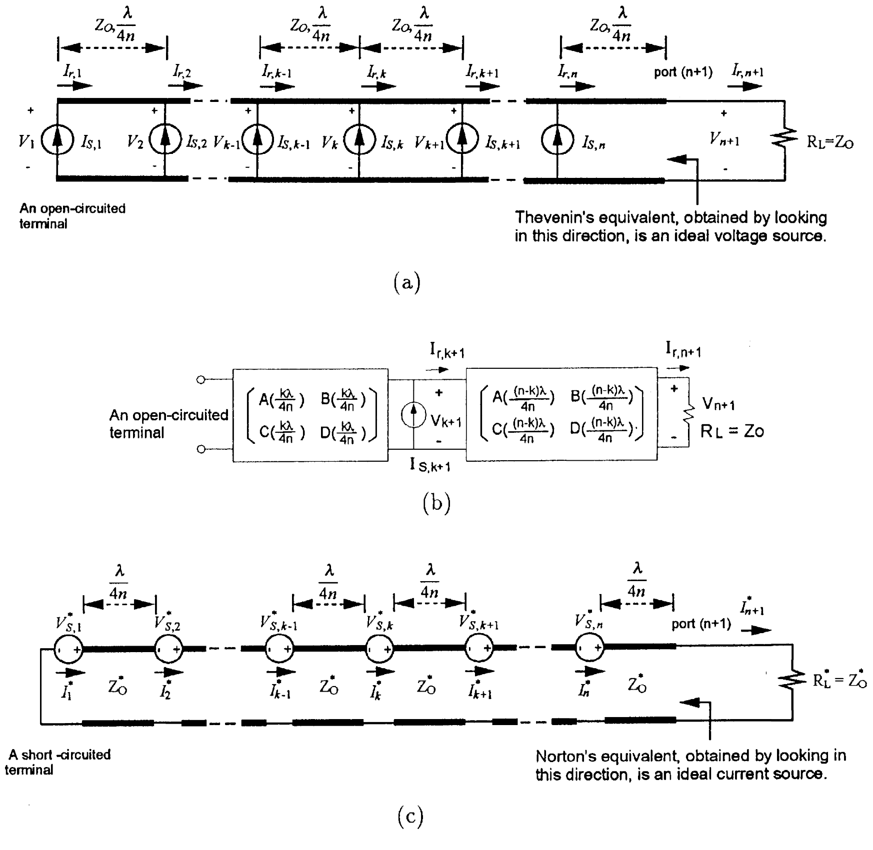

Figure 1. (a) Transmission-line-type voltage source (TLT-VS). (b) The equivalent circuit is obtained by only considering the individual source $I_{S,k+1}$. (c) Transmission-line-type current source (TLT-CS)

2.2. *TL-type current source*

The algorithm for finding the topological dual is well known and can be found in texts on the duality transformation of basic network theory.[8] The duality principle operates on a network of two-terminal elements to produce another network with the same number of elements. The original and transformed circuits are said to be duals of each other and their properties are closely related in many ways.

According to the dual transformation, one interchanges the voltage and current wave-forms of the uniform transmission line, i.e. let v be i^* and i be v^*, and simultaneously the value of Z_O^* equals that of Z_O^{-1}. As a result, the dual of a transmission line with characteristic impedance Z_O is also a transmission line with characteristic impedance Z_O^* numerically equal to Z_O^{-1}, which has the same two-port equations as (1) but its *ABCD* matrix with $A(l) = D(l) = \cos(2\pi l/\lambda)$, $B(l) = \mathrm{j}Z_O^* \sin(2\pi l/\lambda)$ and $C(l) = \mathrm{j}Y_O^* \sin(2\pi l/\lambda)$.

The transmission-line-type current source (TLT-CS) can be derived from the TLT-VS by utilization of the duality algorithm, as illustrated in Figure 1(c), where the phasor voltage of every source is V_S^* and the terminal R_L^* equals Z_O^*. It is emphasized that since the input impedance looking towards the transmission line of length $l = \lambda/4$ with a short-circuited terminal at port $n + 1$ is equal to infinity, the TLT-CS acts as an ideal current source with phasor current I_{n+1}^* with respect to the $(n + 1)$th port. The relationship between I_{n+1}^* and V_S^* for the TLT-CS can be obtained by interchanging the voltage and current wave-forms in equation (3):

$$I_{n+1}^* = -\mathrm{j}\,\frac{1}{2Z_O^*}\left[\cot\left(\frac{\pi}{4n}\right) + 1\right]V_S^* \tag{4}$$

The phasor current I_{n+1}^* through R_L^* is proportional to the total number of sources.

3. ONE-DIMENSIONAL COLLECTION SYSTEMS

3.1. *Current-type collection system*

Figure 2(a) shows the collection system with distributed current sources, called the current-type transmission line collection system (CT-TLCS), where the transmission line is matched with both load

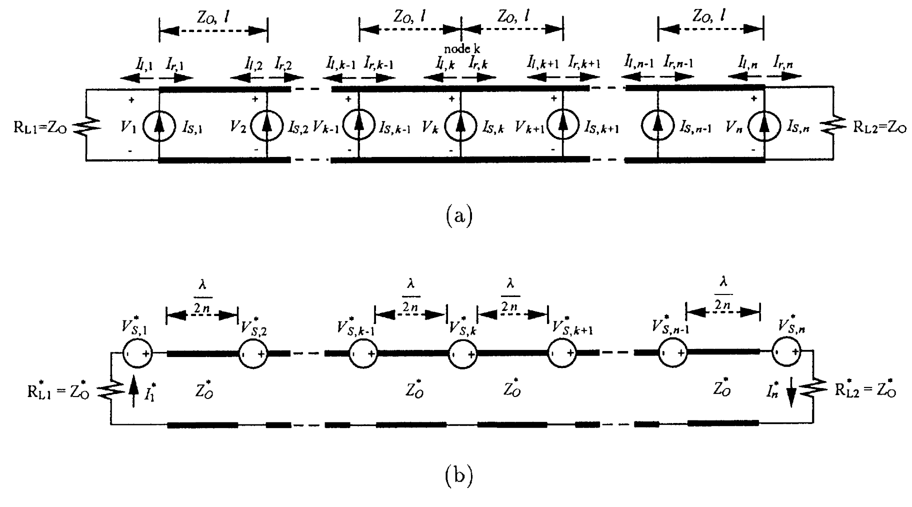

Figure 2. (a) Current-type transmission line collection system (CT-TLCS). (b) Voltage-type transmission line collection system (VT-TLCS)

terminals, i.e. $R_{L1} = R_{L2} = Z_O$. The CT-TLCS was presented in Reference 9 and here we state only its important aspects.

1. By letting $I_{S,k} = I_m e^{jk\theta}$ and $\beta l = \theta$, the phasor voltage drops at R_{L1} and R_{L2} are V_1 and V_n, respectively, given by

$$V_1 = \frac{n}{2} Z_O I_m e^{j\theta} \quad (5)$$

$$V_n = \frac{1}{2} Z_O I_m (e^{-j(n-2)\theta} + e^{-j(n-4)\theta} + e^{-j(n-6)\theta} + \cdots + e^{jn\theta}) \quad (6)$$

   It is noted that when, $\beta l = \theta = \pi/n$, V_n is equal to zero but V_1 is not, which implies that the CT-TLCS transmits power to R_{L1} but transmits no power to R_{L2}.

2. Similarly, by letting $\beta l = -\theta$, V_1 and V_n are expressed as

$$V_n = \frac{1}{2} Z_O I_m (e^{j\theta} + e^{j3\theta} + e^{j5\theta} + \cdots + e^{jn\theta}) \quad (7)$$

$$V_n = \frac{n}{2} Z_O I_m e^{jn\theta} \quad (8)$$

   The importance is that when $\beta l = -\theta = \pi/n$, V_1 equals zero but $_n$ does not, which implies that the CT-TLCS transmits power to R_{L2} but transmits no power to R_{L1}. In addition, the length l of every subtransmission line notably equals $\lambda/2n$, as derived from $\beta l = 2\pi l/\lambda = \pi/n$.

The renewable power form distributed current sources can be accumulated and propagated towards the target load of R_{L1} or R_{L2} via the CT-TLCS, where the length l of all subtransmission lines is equal to $\lambda/2n$ and the current source $I = I_m e^{jk\theta}$ must satisfy the phase condition $\theta = -\pi/n$ or $\theta = \pi/n$.

3.2. Voltage-type collection system

Based on the duality principle, the voltage-type transmission line collection system (VT-TLCS) can be easily developed from the CT-TLCS, as shown in Figure 2(b), where the phasor representative of the voltage source is $V^*_{S,k} = V_m e^{jk\theta}$ and both terminals satisfy $R^*_{L1} = R^*_{L2} = Z_O$.Note that Z^*_O numerically equals Z_0^{-1} and the value of V_m equals I_m. The voltage and current wave-forms of both transmission line collection systems are interchanged with each other. By controlling the phase degree of θ, the net power flow of the VT-TLCS can be towards R^*_{L1} for $\theta = \pi/n$ or towards R^*_{L2} for $\theta = -\pi/n$. Therefore we can interchange the voltage and current wave-forms in equation (8) and the current I^*_n through R_{L2} for $\theta = -\pi/n$ is given by

$$I^*_n = \frac{n}{2Z^*_O} V_m e^{jn\theta} \quad (9)$$

4. TWO-DIMENSIONAL COLLECTION SYSTEMS

Two-dimensional transmission line collection systems (2D-TLCSs) can be simply derived from the CT-TLCS or VT-TLCS by replacing distributed AC electric sources with TLT-VSs or TLT-CSs. Figure 3 shows the schematic diagram of a two-dimensional voltage-type transmission line collection system (2D-VT-TLCS) in which the main collection system is a CT-TLCS with the distributed AC current sources $I_{S,k} = I_M e^{jk\theta}$ and every distributed AC current source is created by a TLT-CS, where the characteristic impedance of the main TL, denoted by Z_{Om}, is equal to two times that of a sub-TL, denoted by Z_{Os}, i.e. $Z_{Om} = 2Z_{Os}$, and all voltage sources $V_{S,k,h}$ in the kth TLT-CS are identical and determined by substituting $I_{S,k}$ into equation (4). For a given case of $\theta = -\pi/q$ the main collection network accumulates all the average

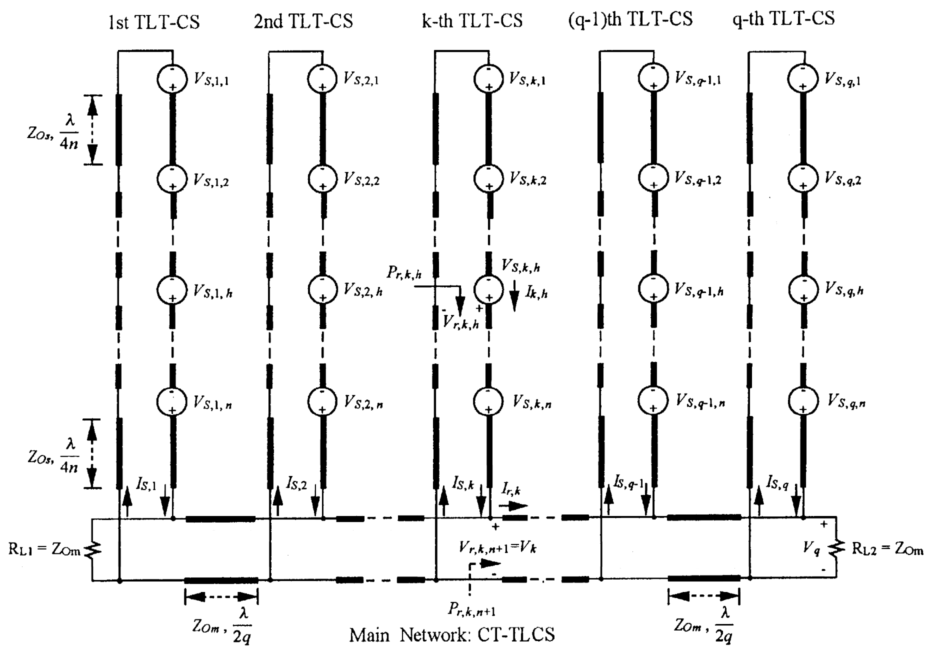

Figure 3. Two-dimensional voltage-type transmission line collection system (2D-VT-TLCS)

power supplied by TLT-CSs towards R_{L2}, but R_{L1} will receive no power, as analysed in Section 3. The phasor voltage V_q across R_{L2} is given by $V_q = (q/2)Z_{Om}I_M e^{-j\pi}$ from equation (8).

Similarly, Figure 4 shows the schematic diagram of a two-dimensional current-type transmission line collection system (2D-CT-TLCS) that adopts a VT-TLCS as the main collection system and constructs every distributed AC voltage source $V_{S,k} = V_M e^{jk\theta}$ in the main VT-TLCS by using TLT-VSs, where

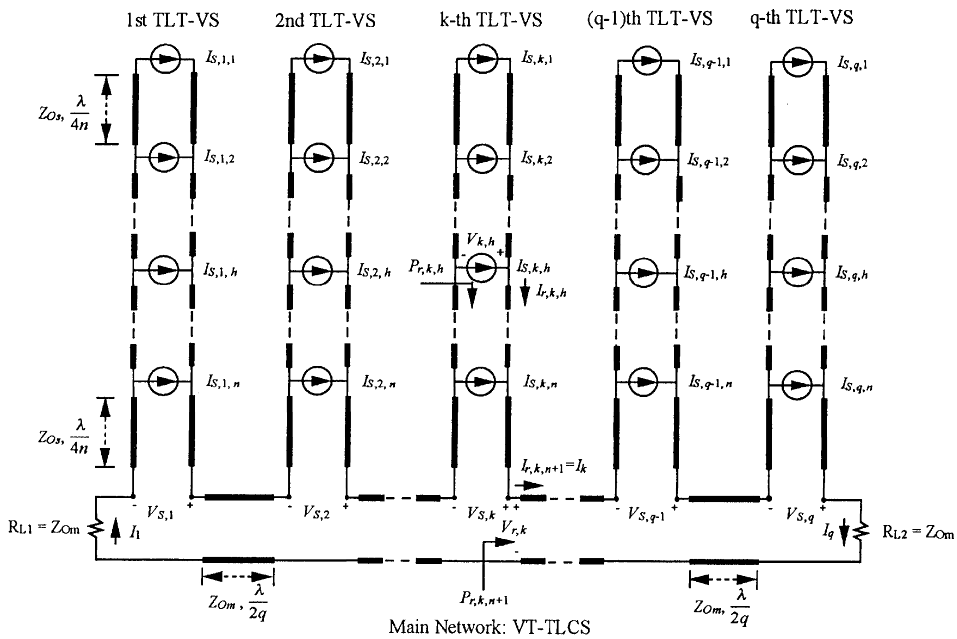

Figure 4. Two-dimensional current-type transmission line collection system (2D-CT-TLCS)

$Z_{Om} = \frac{1}{2} Z_{Os}$, and all current sources $I_{S,,k,h}$ in the kth TLT-VS and $V_{S,k}$ have the relationship of equation (3). It should be pointed out that the 2D-VT-TLCS and 2D-CT-TLCS are duals of each other.

In Figure 3, the $P_{S,k,h} = \frac{1}{2} V_{S,k,h} \bar{I}_{k,h}$ is defined as the complex power supplied by the voltage source $V_{S,k,h}$ where $I_{k,h}$ is the current through the voltage source $V_{S,k,h}$. $P_{r,k,h} = \frac{1}{2} V_{r,k,h} \bar{I}_{k,h}$ is also defined as the complex power looking towards the main network at the kth TLT-CS. Moreover, $P_{r,k,n+1} = \frac{1}{2} V_{r,k,n+1} \bar{I}_{r,k} = \frac{1}{2} V_k \bar{I}_{r,k}$ is defined as the complex power looking towards R_{L2} in the main network CT-TLCS. Figure 5 shows the simulated results of a 2D-VT-TLCS with $Z_{Om} = 50\ \Omega$, $Z_{Os} = 25\ \Omega$, $n = 9$, $q = 10$ and $I_{S,k} = 10e^{-j} k\pi/q$ amps. The target load R_{L2} is at $(k, h) = (q, n+1) = (10, 10)$. The voltage magnitude $|V_{r,k,h}|$ in the kth TLT-CS has a minimum at $h = 1$ and a maximum at $h = 10$, as shown in Figure 5(a). In contrast, the minimum and maximum of the current magnitude $|I_{k,h}|$ through the voltage source occur at $h = 10$ and $h = 1$ respectively,

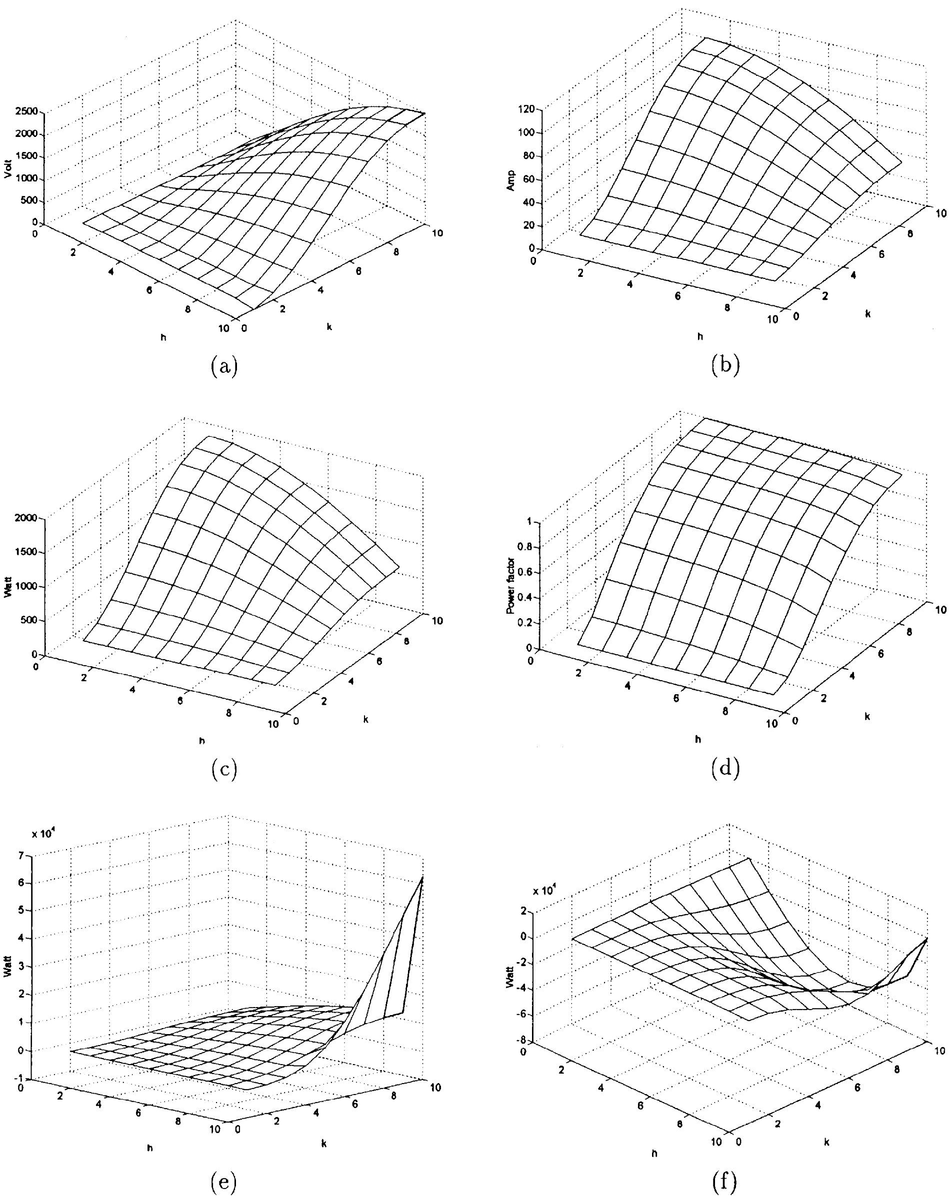

Figure 5. Simulated results of 2D-VT-TLCS with $Z_{Om} = 50\ \Omega$, $Z_{Os} = 25\ \Omega$, $n = 9$, $q = 10$ and $I_{S,k} = 10e^{-j(k\pi/q)}$ amps: (a) magnitude of $V_{r,k,h}$; (b) magnitude of $I_{k,h}$; (c) magnitude and (d) power factor of $P_{S,k,h}$; (e) real part and (f) imaginary part of $P_{r,k,h}$

as shown in Figure 5(b). As observed from Figures 5(c) and 5(d), the power rating and power factor supplied by the voltage source $V_{S,k,h}$ increase as the location of the TLT-CS becomes closer to the target load R_{L2}. It should be stressed that the 2D-VT-TLCS can automatically accumulate the distributed electric energy towards the target load R_{L2} along the transmission line network and into a large power flow at the target, as illustrated by Figure 5(e).

It is emphasized that the two-dimensional transmission line collection systems in Figures 3 and 4 really accumulate the power from distributed renewable energy sources towards the target load and incur less costs, because larger voltage/current and power rating are required for only some AC electrical sources and transmission lines.

5. CONCLUSIONS

This paper proposes one-dimensional and two-dimensional transmission line collection systems for automatically accumulating power from renewable energy, which is distributed over a very large region, into a large power flow at the target load. Both current-type and voltage-type transmission line collection systems for accumulating the distributed renewable power have been discussed in this paper. Based on transmission line theory and controlling the phase of AC sources, the net electrical power of the proposed transmission-line-type networks can flow towards the target load. Moreover, the proposed novel 2D-VT-TLCS and 2D-CS-TLCS incur less costs, because only those sources which are far from the target load and those transmission lines which are close to the target load are required to have larger power rating.

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