RF VECTOR CONTROL FOR EFFICIENT FAN-OUT POWER DISTRIBUTION *

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Abstract

Distributing RF power of a generator to many cavity loads is often considered in RF linacs for possible cost reduction and simplification of system. If the amplitude and phase of the power delivered to individual cavity have to be controlled precisely, using fixed power splitting system may not be satisfactory. An approach for fan-out RF power distribution using transmission line circuit parameters for achieving full vector control and maximum power efficiency is considered. This fan-out distribution approach can provide required RF power to the cavities by adjusting the transmission line phase delays between the cavities and reactive loads at the cavity inputs. In this approach, the phase delays and the reactive loads become the RF control parameters for delivering a set of required cavity RF voltages for an entire system.

INTRODUCTION

Many high power RF accelerators may have to drive one cavity with one RF generator if independent and accurate RF vector control is required. Fan-out power distribution system feeding many cavities with a high powered generator can be useful for large scale high powered systems, especially for SRF ion accelerators, to reduce construction costs and save on operating costs. Various RF power distribution systems have been used and proposed in [1] and often pulse compression is combined for short pulse systems. Mechanically variable directional couplers are employed for an adjustable distribution [2]. RF distribution systems using high power vector modulators have been considered for fast control [3]. Using a vector modulator at a cavity input with a fixed power splitting requires more power than the power required in the cavity to enable adequate RF control.

A fan-out distribution presented in this paper can use only the power required to maintain right RF voltages in the cavities with a transmission line network. This approach can maximize the RF power to beam efficiency of a fan-out system. The multi-cavity system is controlled as a whole for various operation condition of the accelerator. The vector control is done by adjusting phase delays between the load cavities and reactive loads at cavity inputs. The reactive loads and transmission line phase delays can be realized using high power RF phase shifters.

Figure 1(a) shows an arbitrary fan-out power distribution system for a particle accelerator with N cavities. There can be various ways to construct a fan-out power distribution system using a transmission line network: one approach is shown in Figures 1(b) with the loads connected in parallel to the transmission line and 1(c) with the loads connected in series. The two types of connections may be mixed if construction and operation can benefit.

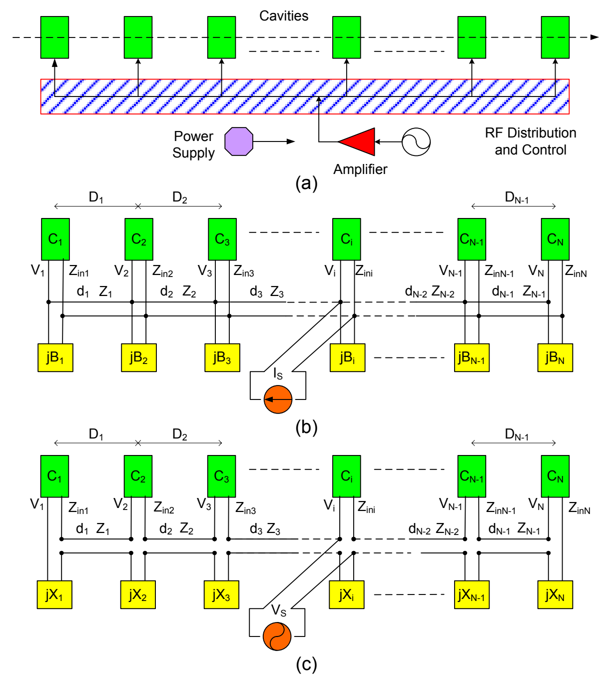

Figure 1: (a) Generalized high power RF distribution in a multi-cavity accelerator, (b) using transmission line network with loads and control elements connected in parallel, (c) using transmission line network with loads and control elements connected in series.

DEVELOPMENT

The transmission line network shown in Figure 1(b) can be synthesized and analyzed using short-circuit admittance parameters and the network in Figure 1(c) can be treated using open-circuit impedance parameters similarly [4]. Although either one of the approaches can be used, it seems the parallel connection can be more practical in using various transmission lines. The design in Figure 1(b) using the short-circuit admittance parameters is discussed in the following.

Generally, in an accelerator, the cavity input impedances and the required load voltages are known for an operating condition. Therefore, in a network shown in Figure 1(b), any two of the three unknown parameters, transmission line characteristic impedance, Z_i, electrical length between the two neighboring loads, d_i, and the reactive loads, B_i can be varied for having the required

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voltages at the cavities. Among the above possibilities, the most practical way of having adjustable transmission line network is to have a uniform characteristic impedance Z_o ($Z_i = Z_o$ *for* $i=1,.., N-1$) and find d_i and B_i.

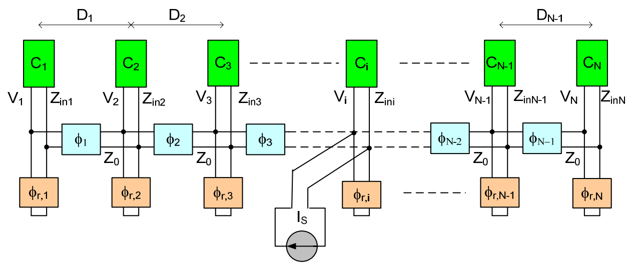

Figure 2 – A fan-out power distribution system in Figure 1(b) realized using phase shifts in transmission line phase delays and reactive loadings

In Figure 1(b), N cavities are fed by a single generator at the *i-th* terminal through a transmission line network. D_i is the physical spacing between two neighboring cavities, V_i is the voltage delivered to the cavity input, Z_i is the transmission line characteristic impedance, and $Z_{in,i}$ is the cavity input impedance. If $[V^P]$ is a set of voltages for a specific cavity excitation at a time, the phase delays through the transmission line sections between the cavities and the reactive loads that can deliver $[V^P]$ can be found. The transmission line delays (lengths) and reactive loads can be realized by using phase shifters as shown in Figure 2 with phase shifts $\phi_n^T = \beta d_n$ and $\phi_n^L = \cot^{-1}(-B_n/Y_o)$, respectively.

Formulation

Using the short-circuit admittance parameters [Y], the whole network admittance matrix $[Y^S]$ can be constructed and the terminal currents $[I^S]$ and the terminal voltages $[V^P]$ are related as

$$\left[I^S\right]=\left[Y^S\right]\left[V^P\right] \tag{1}$$

where $[Y^S]$ is the short-circuit terminal admittance matrix of the whole system that can be expressed as

$$\left[Y^S\right]=\left[Y^P\right]+\left[Y^T\right]+\left[Y^L\right] \tag{2}$$

where $[Y^P]$ is the input port admittance matrix for the cavities, $[Y^T]$ is admittance matrix of the transmission line network, and $[Y^L]$ is reactive load admittance matrix.

The voltage vectors that are required to maintain a specific voltage distribution over the cavities are

$$\left[V^P\right]^t=\left[V_1 \quad V_2 \quad V_3 \quad \cdots \quad V_N\right] \tag{3}$$

$[I^S]$ contains all zero elements except for the *n-th* terminal that is connected to the generator. The current for the feed terminal is found as

$$Z_f = V_f / I_f \tag{4}$$

where the input impedance Z_f can be found by selecting the element Z_{ii} in the impedance matrix $[Z^S]=[Y^S]^{-1}$. For a system shown in Figure 2, the port admittance matrix for the cavity inputs

$$\left[Y^P\right]=\begin{pmatrix} Y_{in,1} & 0 & \cdots & 0 & 0 \\ 0 & Y_{in,2} & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & Y_{in,N} & 0 \\ 0 & 0 & \cdots & 0 & 0 \end{pmatrix} \tag{5}$$

which is simply a diagonal matrix with $Y_{in,ii} = 1/Z_{in,ii}$ since no mutual coupling is assumed between the cavities. The reactive load admittance matrix

$$\left[Y^L\right]=\begin{pmatrix} jB_1 & 0 & \cdots & 0 \\ 0 & jB_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & jB_{N+1} \end{pmatrix} \tag{6}$$

The transmission line admittance matrix

$$\left[Y^T\right]=\begin{pmatrix} -jY_1\cot\beta d_1 & jY_1\csc\beta d_1 & 0 & \cdots & 0 \\ jY_1\csc\beta d_1 & -j(Y_1\cot\beta d_1 - Y_2\cot\beta d_2) & jY_2\csc\beta d_2 & \cdots & 0 \\ 0 & jY_2\csc\beta d_2 & -j(Y_2\cot\beta d_2 - Y_3\cot\beta d_3) & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & -jY_N\cot\beta d_N \end{pmatrix} \tag{7}$$

A system of equations can be established with Eqs (5) – (7) in Eq. (1) and solved for d_i and B_i with a set of given cavity voltages $[V^P]$. The total power delivered to the loads is the sum of real power flow to the loads and must be equal to the output power of the generator. This enables the complete impedance matching of the generator at the feed terminal. Detailed solution procedure for this fan-out approach was outlined in [5].

Note that there can be several different methods to achieve the impedance matching at the *i-th* terminal for the generator input: C_i is connected to the port with the generator as in Fig. 1(b), C_i is removed to construct a simple Y-type connection to the generator, or with C_i one more reactive loading is used at the generator output.

Load Condition

The above solution includes all mutual couplings associated with the multiple transmissions and reflections at and between the cavity terminals. Note that $V_k = 0$ if no power is applied at the *k-th* cavity input. This can be the case for a disabled or a detuned cavity in practical systems.

If a cavity is connected through a transmission line section and not impedance matched, the connecting line section can be included with an additional short-circuit admittance matrix [Y]. Or the mismatch through the transmission line section between the cavity and the terminal can be included by considering the standing wave with a reflection coefficient Γ(z). For a mismatched cavity load, the port admittance matrix at the terminal before the input of a cavity is

$$Y_{in,i} = Y_o \frac{Y_i^c \cos \beta d_i^c + jY_o \sin \beta d_i^c}{Y_o \cos \beta d_i^c + jY_i^c \sin \beta d_i^c} \qquad (8)$$

where Y_o and d_i^c are the characteristic impedance and the length of the transmission line section connects the cavity to the network, respectively; Y_i^c is the cavity input impedance, and β is the phase constant. The voltage standing wave in the transmission line section between the cavity and the terminal is $V(z) = V_o^+ e^{-j\beta z}\{1 + \Gamma(z)\}$ where voltage reflection coefficient is related to load reflection coefficient Γ(0) as $\Gamma(d_i^c) = \Gamma(0)e^{-2j\beta d_i^c}$. The knowledge of the reflection and the field inside the cavity can define the voltage vectors that need to be satisfied for an operating condition.

Example

An example case of the fan-out power distribution system with uniformly spaced 14-cavity loads with a generator connected at the center of the network (at i=8) is considered. No cavity is connected to the terminal with the generator. Each cavity has 50-ohm input impedance and all the transmission line sections have 50-ohm characteristic impedance. All physical distances between two neighboring cavities are set to 1.5m. Two sets of voltages are used and results are compared: (1) a set of voltages for excitation of the cavities are specified for this example and (2) the same voltages except V_{10}=0 to simulate a disconnected or a disabled cavity. The specified voltages and resulting computed phases to achieve the d_i and B_i are shown in Table 1. The frequency of operation is 805 MHz. For B_i a short circuit is assumed at the end of the phase shifter.

Table 1: An example case with 14 loads

Cav	V_i (V)	ϕ for d_i (deg)	ϕ for B_i (deg)	Cav	V_i (V)	ϕ for d_i (deg)	ϕ for B_i (deg)
1	1.0000/09.90°	195.31	53.58	1	1.0000/09.90°	195.31	53.58
2	1.1892/22.74 °	189.22	-89.33	2	1.1892/22.74 °	189.22	-89.33
3	1.3161/37.00 °	186.81	-71.85	3	1.3161/37.00 °	186.81	-71.85
4	1.4142/52.75 °	185.45	-59.54	4	1.4142/52.75 °	185.45	-59.54
5	1.4953/68.30 °	184.58	-49.99	5	1.4953/68.30 °	184.58	-49.99
6	1.5651/85.00 °	184.01	-42.51	6	1.5651/85.00 °	184.01	-42.51
7	1.6266/102.27 °	133.68	46.97	7	1.6266/102.27 °	136.19	44.40
(8)	6.1352/0 °	162.95	11.27	(8)	5.8718/0 °	161.21	11.90
9	1.7321/138.27 °	177.34	4.45	9	1.7321/138.27 °	179.95	0.02
10	1.7783/156.90°	176.66	24.98	10	0.0000	179.95	0.00
11	1.8212/175.92 °	175.60	30.31	11	1.8212/175.92 °	175.60	0.02
12	1.8612/195.28 °	173.86	37.91	12	1.8612/195.28 °	173.86	37.91
13	1.8988/214.96 °	170.48	49.66	13	1.8988/214.96 °	170.48	49.66
14	1.9343/234.96 °	160.05	70.94	14	1.9343/234.96 °	160.05	70.94
15	1.9680/255.24 °		86.94	15	1.9680/255.24 °		86.94

The specified cavity input voltages in this example have fairly large variations both in amplitude and in phase. It is seen that setting a zero voltage for a cavity changes the d_i and B_i only around the affected terminals between the cavity and the generator. The voltage at the feed terminal, V_8 shows the voltage for the total power from the generator.

DISCUSSION AND CONCLUSION

In this fan-out distribution, one control system needs to govern all cavities in a network as a whole. Since the system is designed to deliver only the power needed in the cavities, the output power of the generator needs to be controlled. If the cavities are excited with beam and thus the beam induced voltages appear at the cavity input couplers, the required voltage vectors can be redefined accordingly. The approach can be applied to various multi-cavity accelerators including the energy recovery linacs.

Although the power density in the transmission line becomes greater if it is closer to the generator input in the network, the maximum power allowed in the transmission lines are usually comparable to the maximum power available from the high power generators. For practical transmission line junctions at the network nodes, modification of the system admittance matrices will be needed. The phase delays and reactive loadings can be realized by using fast high power fast phase shifters for fast vector control of RF voltages. The control can still be done using any mechanical phase shifters if it is acceptable for a system. For a practical multi-cavity system using the proposed fan-out distribution, matching low-level RF control system needs to be developed.

The proposed system can eliminate the requirement of extra power in fixed power distribution systems so that operation efficiency can be maximized. The method presented here can also be used with more than one single generator, making the system more redundant in certain applications.

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