Non-Foster Reactance Matching for Antennas

White Paper
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1 Introduction

Electrically small antennas have significant capacitive reactance along with small radiation resistance values. A simple model for such an antenna is a series RC circuit. The large capacitive reactance acts to store much of the energy input to the antenna instead of allowing it to radiate. Matching a 50-Ω source to the high capacitance and low resistance present some real challenges. The typical approach is to negate the negative reactance with an inductive match and to transform the resistance. This approach can provide a very good match at a single frequency. Unfortunately, matching well over an appreciable bandwidth for this size of antenna is difficult, if not impossible, to achieve with standard passive elements. The resistance in the non-ideal inductors, among other factors, can cause high temperatures within the matching network and lead to physical failure. This case is exacerbated within the HF band since transmitters are often rated a minimum of 100 W.

This paper will address two possible techniques to reduce the capacitive reactance of an electrically small antenna and, hence, improve its radiation characteristics. The first method is to use a negative impedance converter (NIC) constructed from active and passive circuit elements as a way to tune out the antennas reactance between the source and the antenna. The second method is to embed the antenna in a double negative material (DNG), which would change the impedance of the antenna itself, with the end result of tuning out some of the unwanted reactance seen by the source.

2 Using a NIC for Antenna Impedance Matching

The definition of a NIC is quite simple: it is a two-port device with an input impedance that is the negative of the output impedance connected to its output port; $Z_{in} = -Z_{out}$. This impedance transformation comes at the price of using active elements in the construction of the NIC. This section will discuss why an element with a negative impedance might be useful along with some general issues concerning negative impedance converters.

Assume a simple circuit of a voltage source and a source resistance R_s and a load consisting of a series capacitor C_L and resistor R_L. This load impedance is $Z_L = R_L - jX_L$, where $X_L = 1/(\omega C)$. The capacitive reactance X_L could be tuned out at a single frequency by inserting a series inductor into the circuit. Instead, assume that there exists an element that has an impedance of $X_n = 1/[\omega(-C)]$, thus a negative capacitance. Then $X_L = -X_n$ and, putting this in series with the load, yields an input impedance of $Z_{in} = R_L - jX_L - jX_n = R_L - jX_L + jX_L = R_L$. Note that, if XL $\approx -X_n$ over an appreciable frequency range, a match can be achieved over a considerably wider bandwidth than with a series inductor. The NIC can provide this function over some finite bandwidth

In general, impedance matching problems seek to both tune out unwanted reactance of a given load impedance and simultaneously transform the remaining resistance to that of the input resistance of the source. The solution to this problem is highly bandwidth dependant. The Bode-Fano criteria stipulate that there is a tradeoff between the level of match between load and feed and the bandwidth over which the impedance match is adequate. In many applications, this is a fairly easy tradeoff to make. Unfortunately, in the case for a small antenna, the large capacitive reactance makes the trade-off quite difficult. Using a small number of matching elements to tune out the reactance would provide too small a useable bandwidth. Alternatively using many elements to provide for a useful bandwidth would introduce too much loss into the system, again providing an unusable solution. It is in this application that a NIC can be of potential use.

There have been several recent papers investigating this application [1][2]. Constructing a NIC requires the use of active devices. The original design is that of Linvill [3] which consists of 2 npn BJT's and several resistors. [4] and [5] discuss the details of designing a NIC. It is also possible to construct a NIC using an Op-Amp [6][7].

When using a NIC, stability and active device over-drive must be taken into account. In the above example of a series-connected NIC, with a capacitor on the output of the NIC, it is possible that some parasitic resistance, in either the active devices of the NIC or the capacitor, will show up at the input port as a negative resistance. If this negative resistance is larger than the series resistance of the remaining circuit elements, the NIC could become unstable. Overdriving the active devices of the NIC can also be an issue in the context of a transmitter. As mentioned above, a NIC is comprised of active devices that must be DC biased. A large signal from a transmitter into the NIC can force the active devices into nonlinear operating regions, with undesirable results.

3 Using a DNG to Mitigate Antenna Reactance

A double negative material is one in which the permittivity and permeability are both less than zero. These types of materials were presented theoretically almost 40 years ago and more recently have been getting quite a bit of attention. Thus far, no material possessing this double-negative quality has been found in nature; all double-negative materials are man-made, i.e., metamaterials. The principle attributes of DNG materials are that an electromagnetic wave will refract in the opposite direction to that of a standard double positive (DPS) material, and that the wave vector and the Poynting vector are anti-parallel. In the last 10 years or so, researchers have sought to use DNG's to improve the performance of electrically small antennas.

Some studies have recently been conducted [8][9] which indicate that, by embedding an electrically small antenna inside a DNG shell, the transmitted power of the antenna is increased. It is demonstrated that the DNG shell acts as a kind of impedance match that reduces the large capacitive reactance of the small antenna. Given the potential overdrive issues when using a NIC with an electrically small antenna in transmit mode, applying a DNG might be appropriate.

As stated, a DNG material is man-made. Many times the construction consists of embedding metal particles into an otherwise homogeneous medium. These particles can take many different shapes and sizes from small metal cylinders to flat ring resonators [10][11]. This can be a potentially difficult task and a potential risk. There are no commercial vendors at present who provide DNG materials. The basic area of NICs has been around for a fairly long time and is only now coming to a point of feasibility, primarily due to technology. In a similar manner, metamaterials have been in use for many years, but have only recently become a major interest in reduction of antenna size. This work would address the feasibility and limitations of the technology for antenna applications.

4 Time frame and Deliverables

VTAG proposes to investigate the application of including NIC in the matching network of electrically small antennas. The center frequency of interest is 20 MHz, and a short monopole will be initially considered. VTAG will develop a prototype NIC for this task. The antenna and matching network will be investigated first in receive mode and followed by transmit mode. Tuning of the NIC design and component selection for stable operation is the focus of Task 1. Protections of the DC biasing in the active NIC elements are a large part of this. VTAG will complete network analyzer and antenna range tests on (classically) inductively tuned monopole and the NIC monopole.

Following the successful completion of Task 1, VTAG will analytically and numerically investigate the application of a DNG cylinder to surround the Task 1 monopole. We will parametrically investigate variations to the cylinder geometry, and trade-offs between performance and the feasibility of manufacturing the DNG shape and its thickness will be discussed. We will search for a DNG geometry that is more amenable to fabrication (Task 3). The performance of the DNG monopole will be evaluated against the results from Task 1 to determine if follow-on DNG fabrication and testing holds a potentially valuable outcome.

In Task 3, VTAG will coordinate the development of a DNG shell for the monopole. Other labs within Virginia Tech's ECE Department are actively researching DNG materials. VTAG will partner with them to develop a single DNG for the monopole's shell. Task 3 is inherently more risky because of the current state of technology.

In Task 4, VTAG will mate the developed DNG material with the monopole and complete network analyzer and antenna range tests on it. Performance comparisons will be laid out between the (classically) inductively tuned monopole, the NIC monopole, and the DNG monopole.

Tasks 3 and 4 depend on the availability of DNG developed material and might not be considered in an initial study.

5 References

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